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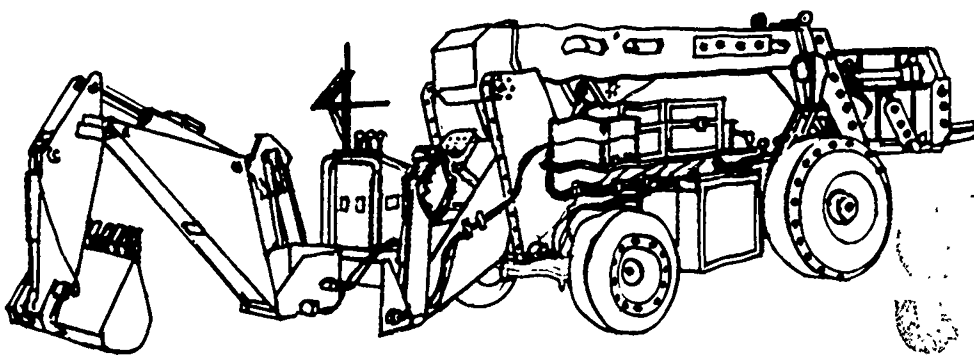
Technical Report

ADVANCED MATERIAL HANDLING EQUIPMENT CONTROLS



ABSTRACT In order to improve the productivity, safety, and reliability of Marine Corps Material Handling Equipment (MHE) in a combat environment, this investigation was divided between two specific aspects of MHE operations. The predominant of these is "High Speed Control" (HSC). This concept involves the coupling of high flow hydraulics with an appropriately synthesized feedback control network in order to achieve system dynamic response two to three times faster than that achieved with conventional control systems, along with rapid convergence (seemingly critical damping following command signal crossover). The second aspect of MHE operations investigated is the enhancement of palletized cargo acquisition from ISO containers using the Marine Corps Extendable Boom Forklift (EBFL). Enhancement is by way of providing the EBFL operator with a stereoscopic (three-dimensional) video image, inside the cab, of the cargo-acquisition area, showing both the cargo pallet slots and the forklift tines. Subsequently, computer control can be integrated with the video image processing so as to facilitate or automate acquisition.

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METRIC CONVERSION FACTORS

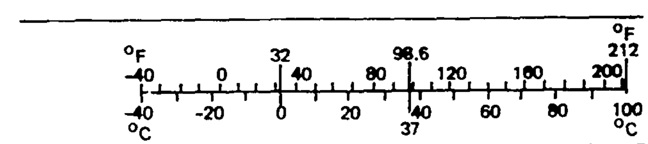
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10 286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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In order to improve the productivity, safety and reliability of Marine Corps Material Handling Equipment (MHE) in a combat environment, this investigation was divided between two specific aspects of MHE operations. The predominant of these is "High Speed Control" (HSC). This concept involves the coupling of high flow hydraulics with an apppropriately synthesized feedback control network in order to achieve system dynamic response two to three times faster than that achieved with conventional control systems, along with rapid convergence (seemingly critical damping following command signal crossover). The second aspect of MHE operations investigated is the enhancement of palletized cargo acquisition from ISO containers using the Marine Corps Extendable Boom Fork-lift (EBFL). Enhancement is by way of providing the EBFL operator with a stereoscopic three-dimensional video image, inside the cab, of the cargo-acquisition area, showing both the cargo pallet slots and the fork lift tines. Subsequently computer control can be integrated with the video image processing so as to facilitate or automate acquisition.

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For your convenience, the last page of this
report (Appendix C) contains
a list of the abbreviations and acronyms used herein.

CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

Requirements for logistic support within the U.S. Marine Corps (USMC), particularly material handling equipment (MHE), are becoming increasingly stringent as a direct result of the development of new and advanced strategies for operations scenarios. More than ever, speed and productivity are central issues. The Naval Civil Engineering Laboratory (NCEL) has been tasked by the U.S. Marine Corps (USMC) to investigate methods to enhance the productivity and to lower the logistic support requirements of USMC MHE, primarily through retrofit. This document constitutes the results of this effort and serves as the final technical report on the AOA (Amphibious Objective Area) Material Handling Equipment task, Work Unit Number CF3140.01.210, for which FY90 has been the final year of effort.

2.0 OBJECTIVES

The overall objective of the Advanced MHE Controls task has been to improve Marine Corp MHE, making it capable of moving larger volumes (per unit time) of material, supplies and equipment to combat units across shorelines and into forward areas with greater reliability and survivability than with existing equipment. Improved equipment is expected to demonstrate a reasonable return on investment of R&D funds and procurement funds, along with increased productivity and reduced operator skill level requirements. An increase in operator ability to maintain high productivity levels under stressful conditions for extended work periods is also expected.

The primary objective of the FY90 effort in Advanced MHE Controls has been to evaluate the technical aspects of two selected control concepts identified for their potential to meet the overall objective stated above; these are (1) High Speed Control (HSC) and (2) Computer Aided Load Acquisition System (CALAS). A secondary objective of the FY90 effort has been the implementation of an Equipment Controls Test Bed (ECTB) on the NCEL compound, to serve as a testing and evaluation facility for work in Advanced MHE Controls.

3.0 APPROACH

Advanced control technologies and state-of-the-art efforts in heavy equipment controls have been identified and subjectively evaluated for applicability to Marine Corps MHE. Figure 1 lists several control concepts which have been identified as having the potential to improve Marine Corps MHE productivity and capabilities. These control concepts have been divided into two main categories; (1) end-effector control and (2) vehicle control. The Advanced MHE Controls task has focused primarily on the end-effector control concepts with the majority of the work effort concentrated on High Speed Control and the Computer Aided Load Acquisition System. The term, "end-effector" refers to the tool or fixture mounted on the end of the MHE vehicle boom, such as a fork-lift carriage and tines (on an EBFL) or a bucket (on a backhoe's knuckle-boom).

"End-effector controls" refers to those which directly control position and motion of the end-effector (only) and do not effect the vehicle position or motion. A description of each of the end-effector control concepts listed in Figure 1 follows:

1. Multi-Axis Joystick(s) refers to the control input device(s) directly manipulated by the equipment operator to produce motion of the end-effector. This control configuration provides multiple axis (typically two axes) control of the end-effector from one input lever (joystick) thereby reducing the number of input levers required for end-effector control, and offering a more intuitive control input.

2. Master-Slave control is defined here to be the control of an end-effector that provides a perfectly duplicative scale-modeled relationship between the operator's movements and the end-effector motion. This type of control configuration provides the most intuitive control input as well as the potential for reduced skill level and training requirements.

3. Load/Position Sensing refers to sensing capabilities which provide feedback information to the MHE operator (or computer) concerning the weight, position and stability of the load. This information could be used to reduce cargo and equipment damage. Further, it could serve as input data to a controlling computer for teleoperation or full automation.

4. Repetitive Function Programming refers to the application of artificial intelligence in the programming of MHE vehicles to act autonomously in the performance of repetitive function tasks. This could be beneficial in a hazardous environment where minimum human exposure is required.

5. High Speed Control (HSC) is defined here to be the end-effector hydraulic control necessary to accomplish a dynamic response emulating that of the human arm. This capability implies the coupling of high flow hydraulics with a uniquely synthesized feedback control network.

6. The Computer Aided Load Acquisition System (CALAS) is a control/vision system which incorporates stereoscopic vision and computer graphics to provide an enhanced ability to pick and place cargo with an Extendible Boom Forklift (EBFL).

The Marine Corps EBFL (Figure 2), currently in production, has been the focus of conceptual application studies for advanced controls. The Marine Corps EBFL is to be utilized by combat support and combat service support units for handling cargo and supplies weighing up to 10,000 pounds. In addition it will be required to load and unload ISO standard shipping containers of supplies and ammunition.

- END-EFFECTOR CONTROL
  - Multi-Axis Joystick(s)
  - Master-Slave
  - Load/Position Sensing
  - Repetitive Function Programming
  - *High Speed Control (HSC)*
  - *Computer Aided Load Acquisition System (CALAS)*

- VEHICLE CONTROL
  - Speed
  - Direction
  - Vehicle Stability
  - Retrotraverse (Path Programming)
  - Repetitive Function Programming
  - Guidance & Navigation
  - Drive Train Control
  - Automated Suspension

Figure 1. Candidate MHE control concepts.

Figure 2. U.S. Marine Corps Extendable Boom Forklift (EBFL).

4.0 RESULTS

High Speed Control (HSC) and the Computer Aided Load Acquisition System (CALAS) were selected for development for adaptation to the Marine Corps EBFL. Testing and evaluation of HSC and CALAS was to be accomplished utilizing the Equipment Controls Test Bed (ECTB), which has been designed to accommodate studies of HSC, CALAS and other advanced controls concepts. The ECTB is an EBFL similar to the Marine Corps EBFL. Accomplishments on HSC, CALAS, and the ECTB are described below.

4.1 High Speed Control

The concept of High Speed Control (HSC) evolved from the need to move cargo faster and with less induced shock and vibration than with existing equipment to meet increased operational requirements (i.e. move larger volumes of material, supplies, and equipment faster and with greater reliability and survivability than with existing equipment). This concept may be applied to construction equipment (CE) as well as MHE. HSC, as it applies to Marine Corps MHE, relates to the controllability at high speeds of the end-effector of the Marine Corps EBFL, currently in production. The benefit projected for Marine Corps MHE employing HSC is increased productivity as a result of reduction in cargo acquisition and placement cycle times. This increase in productivity may actually be necessary to satisfy present and future operating requirements of large scale operations. A recent study* of Marine Corps MHE and logistic support requirements of the Assault Echelon (AE) phase of a Marine Expeditionary Force (MEF) indicates the need for the capability to acquire, transport, and place cargo pallets in an average of about four minutes each, regardless of transport distance or terrain roughness.

Figure 3 provides a graphical representation of the concept of HSC. The underdamped and overdamped conventional (system) curves depict the corresponding responses of a simple 2nd order system to a step input command. The HSC curve depicts the response of the same system with an HSC electronic servocontroller in series with the system; the important points to note here are (1) the small overshoot and (2) the rapid convergence or time to reach steady state conditions. This equates to faster end-effector positioning and less induced shock and vibration.

The scope of the HSC task encompassed (1) mathematical development of the concept; (2) developing a computer model to "simulate" the system in operation; (3) constructing a laboratory test model; (4) testing and evaluating the laboratory model. Accomplishments on these HSC efforts are discussed below.

4.1.1 High Speed Control Mathematical Model. Figure 4 depicts the mathematical model (in block diagram form) of the position control system for one degree of freedom of the ECTB extendable boom end-effector. This model provides the essence for dynamic analysis of the system. The blocks within the dashed line represents the analog equivalent of the digital electronic servocontroller, Smart Motion Control Card (SMCC),

*MilSpec, Inc., "Marine Corps Material Handling Equipment Analysis," Cardiff, CA, 20 June 1989.

which will provide the compensation networking for achieving HSC. The Moog controller is an analog servocontroller which provides further compensation capabilities for HSC. The servovalve and hydraulic actuator blocks represent a mathematical description of the dynamic characteristics of those components respectively. The encoder block describes the gain associated with the encoder used for position feedback to the digital electronic servocontroller (see Appendix A for detailed mathematical transfer function derivations for each component).

4.1.2 HSC Computer Model. The mathematical model discussed above has been translated into a computer model using a Computer Aided Control System Design (CACSD) software program (MATRIXx/PC) to facilitate dynamic analysis of HSC. The results of this analysis are depicted graphically in Appendix B.

Results are presented for four configurations of the (extendable) boom translation position control system. These configurations are:

1. ECTB B (Figure B1) - The baseline (uncompensated) control system.

2. ECTB 1 (Figure B6) - Control system with the SMCC in series as driver, quadrupled forward loop gain (k=40), amplifier (k=20) in the outer (SMCC) loop feedback, and a low damping coefficient (1.35).

3. ECTB 2 (Figure B10) - Control system with the SMCC in series as driver, restored forward loop gain (k=10), amplifier (k=20) in the outer (SMCC) loop feedback, and a higher SMCC damping coefficient (3.00).

4. ECTB 3 (Figure B15) - Control system with the SMCC in series as driver, restored forward loop gain (k=10), amplifier (k=20) in the outer (SMCC) loop feedback, and a compromised SMCC damping coefficient (2.00).

The four figures above constitute the closed-loop control system block diagrams for the four configurations described. Accompanying each of these diagrams is an open-loop control system block diagram used to construct a root-locus plot for the purpose of stability analysis. Those diagrams are titled ECTB BA, ECTB IA, ECTB 2A, and ECTB 3A, respectively, and are shown in Figures B4, B8, B13 and B17.

It should be noted that the forward loop integrator block and the feed-forward rate and acceleration block, both provided by the SMCC electronic servocontroller as shown in Figure 4, were omitted from the system. These blocks were originally included in the system, but were found to introduce stability problems which were particularly apparent when determining response to a step command. This is not unreasonable, particularly where the acceleration feed-forward term is concerned, since acceleration is essentially infinite at the corner of the step function.

The (lead) d.c. amplifier ahead of the first summing junction of each closed loop block diagram was inserted as an arbitrary measure to assure that the units of output and input are the same for transient response plots. This is why those plots all show a steady-state value of one (the output here is dimensionless and serves merely as a reference).

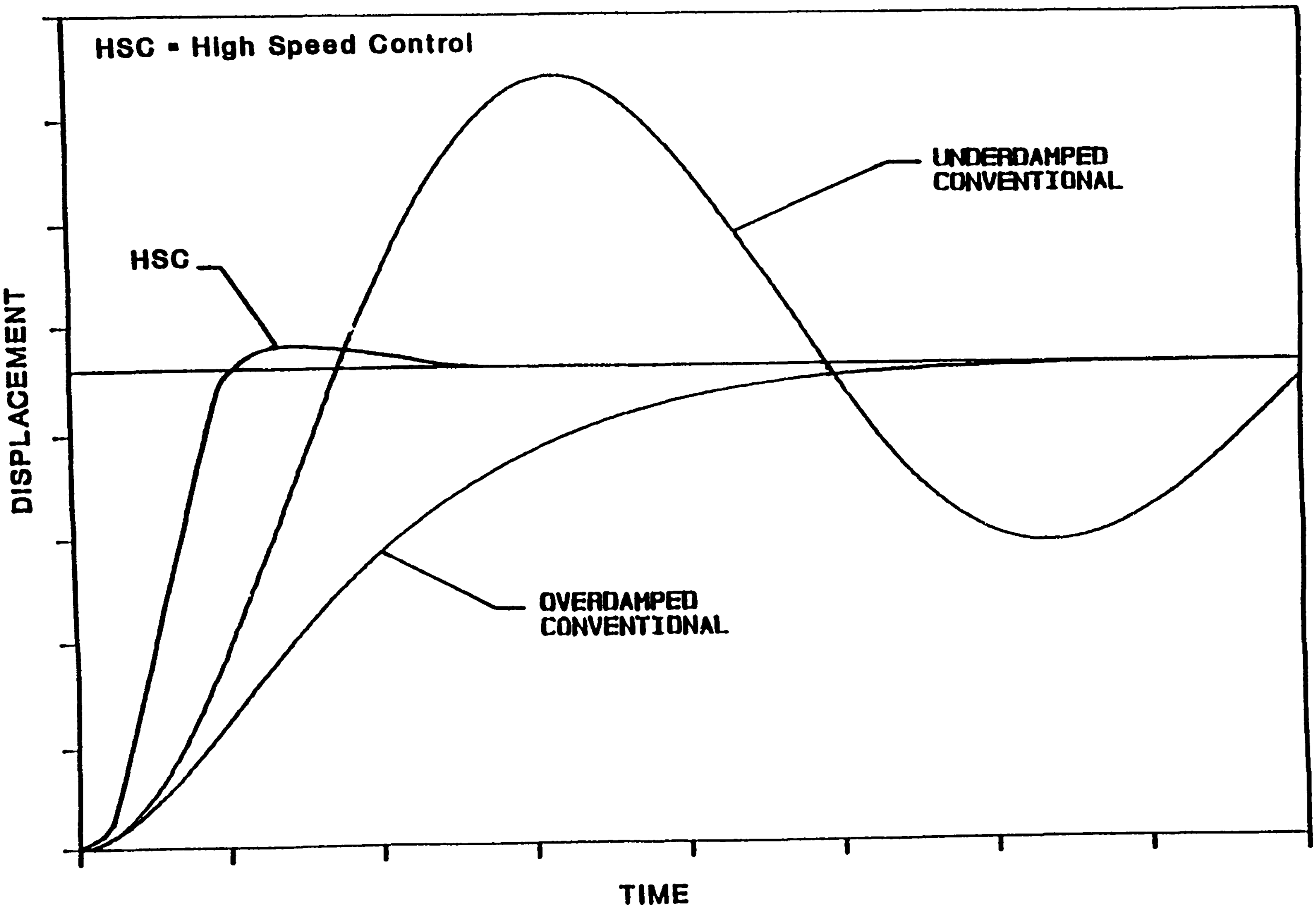
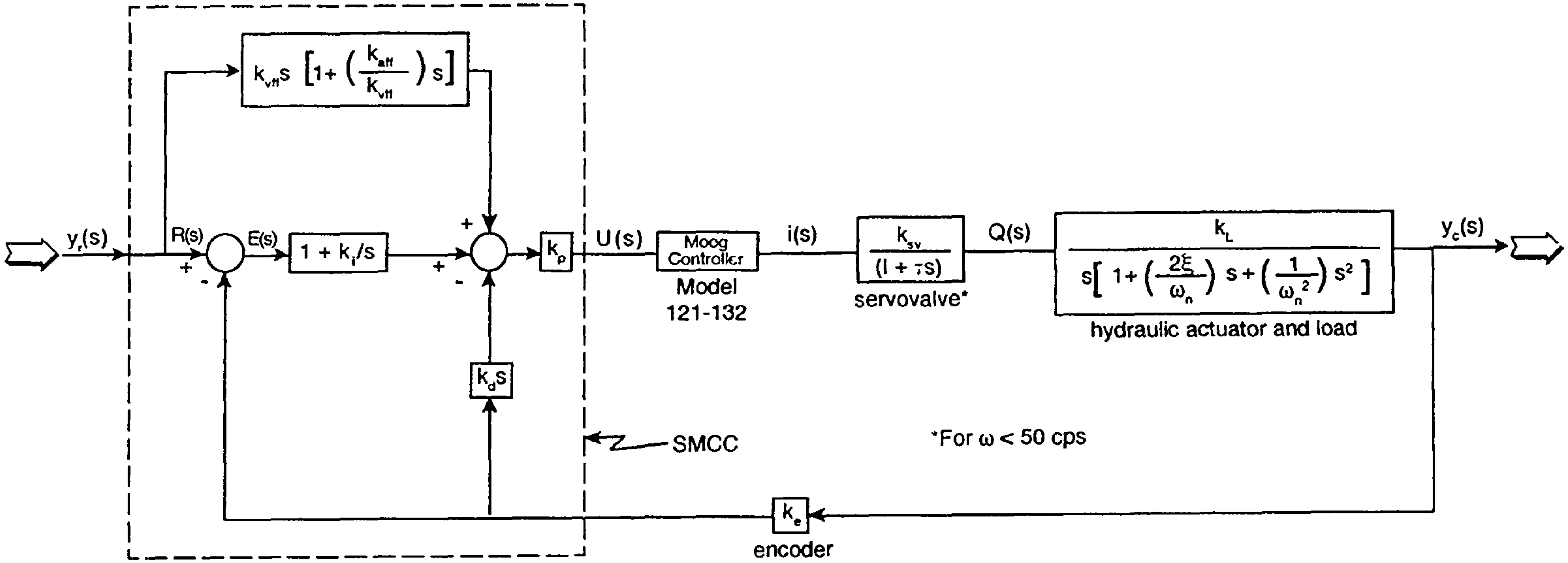


Figure 3. Transient response curves - step input.



LEGEND:

R(s)	reference
E(s)	error in position
U(s)	command output
i(s)	current to servovalve
Q(s)	hydraulic flow from servovalve
$y_c(s)$	end-effector position, controlled
$y_r(s)$	end-effector position, reference

ω_n	natural frequency
τ	servovalve time constant
ξ	damping ratio
k_{vff}	velocity feedforward gain
k_{aff}	acceleration feedforward
k_i	integral gain
k_d	derivative gain
k_p	proportional gain
k_{sv}	servovalve gain
k_L	actuator/load gain
k_e	encoder gain
s	Laplacian operator

NCEL Code L66/WV Miller

Figure 4. EBFL boom position control system block diagram (equipment controls test bed).

However, in plotting the root-locus for each system, it was necessary to ignore the lead amplifier mentioned above in order for the plots to reflect correct values for open-loop gain, hence to provide a correct indication of stability and margin of stability. This is because these lead amplifiers are external to the closed loop, and therefore do not affect either stability or response. Thus, they have been omitted from the open-loop block diagrams.

Root-locus is a convenient means of packing a great deal of system design information into individual plots. Such critical parameters as damping, stability margin and resonant frequencies, all as a function of open-loop gain, are readily obtainable from these plots. Also, they can be used to substantiate results obtained through frequency-response analysis and transient response analysis (response to a step command).

It should also be noted that the boom translation feedback transducer, an optical encoder, has been accurately modeled so as to include the non-linearity associated with its digital (quantized) operation. Even though its resolution (0.006 inches) is relatively fine, it is nevertheless included in the model (rather than ignored), merely as a matter of record.

4.1.3 HSC Computer Simulation Results.

- **ECTB B (baseline system) - Figure B1**: In the transient response simulation (response to a step command), the time to achieve steady state output is 2.8 seconds as shown in Figure B2. The system is slightly underdamped, resulting in a single, very slight (1.5 %) overshoot. The root locus for this system (Figure B5) shows the baseline system to be very stable, not a surprising finding. The dominant poles are, of course, represented by the close-coupled pair on the right side of the plot. The pole pair on the left side of the plot reflects much higher order frequencies which are rarely, if ever experienced, and are obviously always stable. The open loop gain for the baseline system is 1.66 as determined from Figure B5. At the point of locus cross-over into the right half-plane (transition to instability), the system's open loop gain would have to be 29.9, and the gain margin is therefore shown to be 29.9/1.66 = 18.0.

The frequency response plot shown in Figure B3 depicts the closed-loop system performance, and is provided for reference.

- **ECTB 1 - Figure B6**: In the transient response simulation, the time to achieve steady state output showed marked improvement at 0.6 seconds (Figure B7). However, the response is seen to be considerably more oscillatory prior to convergence, due most likely to the quadrupled gain in the forward-path amplifier (k=40).

From the root-locus plot (Figure B9), the system is shown to be unstable, since the closed-loop poles, indicated by small squares, are well into the right half-plane at the open-loop gain of 13.33; cross-over gain is 2.59. This, of course, explains the highly oscillatory nature of the response to a step command (Figure B7).

The ECTB 1 configuration is therefore rejected based on its instability.

- **ECTB 2 - Figure B10**: In the transient response simulation, the oscillatory response has been eliminated by restoration of the forward path amplifier gain (k=10). However, the time to achieve steady state output increased from 0.6 seconds (for ECTB

1) to 1.0 seconds (for ECTB 2), Figure B11. This is no doubt due to the increase in the rate feedback coefficient (damping) from 1.35 to 3.00. This is nevertheless a gross improvement over the transient response for the baseline system (2.8 seconds).

From the root-locus plot (Figure B14), this system is shown to be stable, since the closed-loop poles do reside in the left half-plane, albeit the gain margin is small. The system open-loop gain is 5.55 while the gain at cross-over is 6.60.

The ECTB-2 configuration does meet the High Speed Control objective in that it has a response time shorter than the baseline system by a factor of 2.8:1.0. Figure B19 shows the transient response plots for the baseline system and ECTB-2 so that the reader may make a direct comparison.

The frequency response plot shown in Figure B12 depicts the closed-loop system performance, and is provided for reference.

- **ECTB 3 - Figure B15**: In the transient response simulation, the oscillatory response remains absent, although a slight (1.5 %) overshoot is experienced. However, convergence is rapid, resulting in a time to achieve steady state output of less than 0.5 seconds, Figure B16. This constitutes a reduction in response time of more than 5:1, when compared with the baseline system.

However, from the root-locus plot (Figure B18), the system is shown to be unstable, since the closed-loop poles are in the right half-plane at the open-loop gain of 7.69; cross-over gain is 5.22.

The ECTB 1 configuration is therefore rejected based on its instability. It is possible that with some additional effort on network compensation, or variation in servo-controller coefficients, the transient performance depicted for ECTB 3 could be realized with a stable system.

4.1.4 HSC Laboratory Test Model. Laboratory tests of HSC were to be accomplished utilizing the ECTB under construction at the time of this report. The ECTB is equipped with high flow, high pressure servovalves, electronic servocontrollers, and position feedback encoders to provide the capability to test HSC (ECTB specifications and capabilities are outlined in section 4.3 below). Testing and evaluation of HSC on the ECTB was to include: (1) programming and tuning requirements of the servocontroller cards for optimum system performance; (2) evaluation of end-effector dynamic response characteristics with and without HSC compensation under various material handling operations; (3) evaluation of human operator adjustment to system performance with HSC compensation; (4) productivity comparison studies (i.e., changes in productivity due to HSC compensation).

4.2 Computer Aided Load Acquisition System

NCEL has been conducting research into the development of a Computer Aided Load Acquisition System (CALAS) to be implemented on Marine Corp MHE to improve operational capabilities and productivity. The initial focus of this effort has been on the development of a real time stereoscopic (three-dimensional) vision system to be fitted to the Marine Corps EBFL to enhance the operators view of the end-effector and target load, thereby enhancing the operators ability to pick and place cargo.

The primary function of the Marine Corps EBFL, within the operational scenario, will be the loading and unloading of 20 foot long ISO containers carrying all classes of cargo. A significant problem is encountered in this container unloading operation; the time consuming load acquisition process, resulting from poor (sometimes non-existent) operator visibility of target load slots, causes a significant decrease in EBFL productivity. Operator visibility within the container can be impaired to the degree that a spotter is required within the container to aid the operator in cargo acquisition

The objective has been to develop a computer based system which will increase EBFL productivity and operational safety for the container loading and unloading operations. This objective will be realized through faster load acquisition and through elimination of spotters from the load/unload operations.

4.2.1 Recommended 3-Phase CALAS. NCEL has recommended that CALAS be accomplished in three major phases. Phase I involves the design, component procurement, fabrication, installation and demonstration of a stereoscopic vision system which provides the operator with a close-up three dimensional view (on an in-cab monitor) of the target load and the end-effector tines. This system shall utilize a high resolution stereoscopic camera pair and a high resolution color monitor to provide a video image to the operator to aid in cargo acquisition. This vision enhancement would enable the operator to more easily identify and engage the target load slots.

Phase II would provide computer enhancement to the phase I system through integration of a computer with the video feedback from the stereoscopic camera pair. The computer would provide two dimensional graphic overlays superimposed on the monitor video image, indicating target load slots and end-effector tine outlines, with arrows providing directional assistance to the operator to aid in load acquisition. Figure 5 provides an artist's conception of phase II of CALAS.

Phase III, the final phase, would provide an upgrade to the phase II system to achieve autonomous load acquisition. This would be accomplished through integration of the phase II system with the end-effector controls. The result would be a stereoscopic vision system which has a computer, integral with the video feedback and with the end-effector controls, which would provide automated load acquisition on command from the operator.

4.2.2 CALAS Technology and Teleoperation. Remotely controlled heavy equipment of all types is rapidly becoming a necessity for military operations. Future equipment will quite probably be controlled by operators located at great distances from the equipment they control. Through remote sensing devices and direct sensory (audio and video) feedback, equipment operators of the future may receive images, sound, and graphic overlays in real time, which enable the control of robotic manipulators or unmanned vehicles at great distances. The technology behind CALAS is necessarily a building block in the development of such control systems of the future. This can be seen through the following important aspects of CALAS:

1. The real time stereoscopic video feedback associated with CALAS is important for teleoperation in an unstructured environment in that the remote operators perception of depth is essential for fast accurate control.

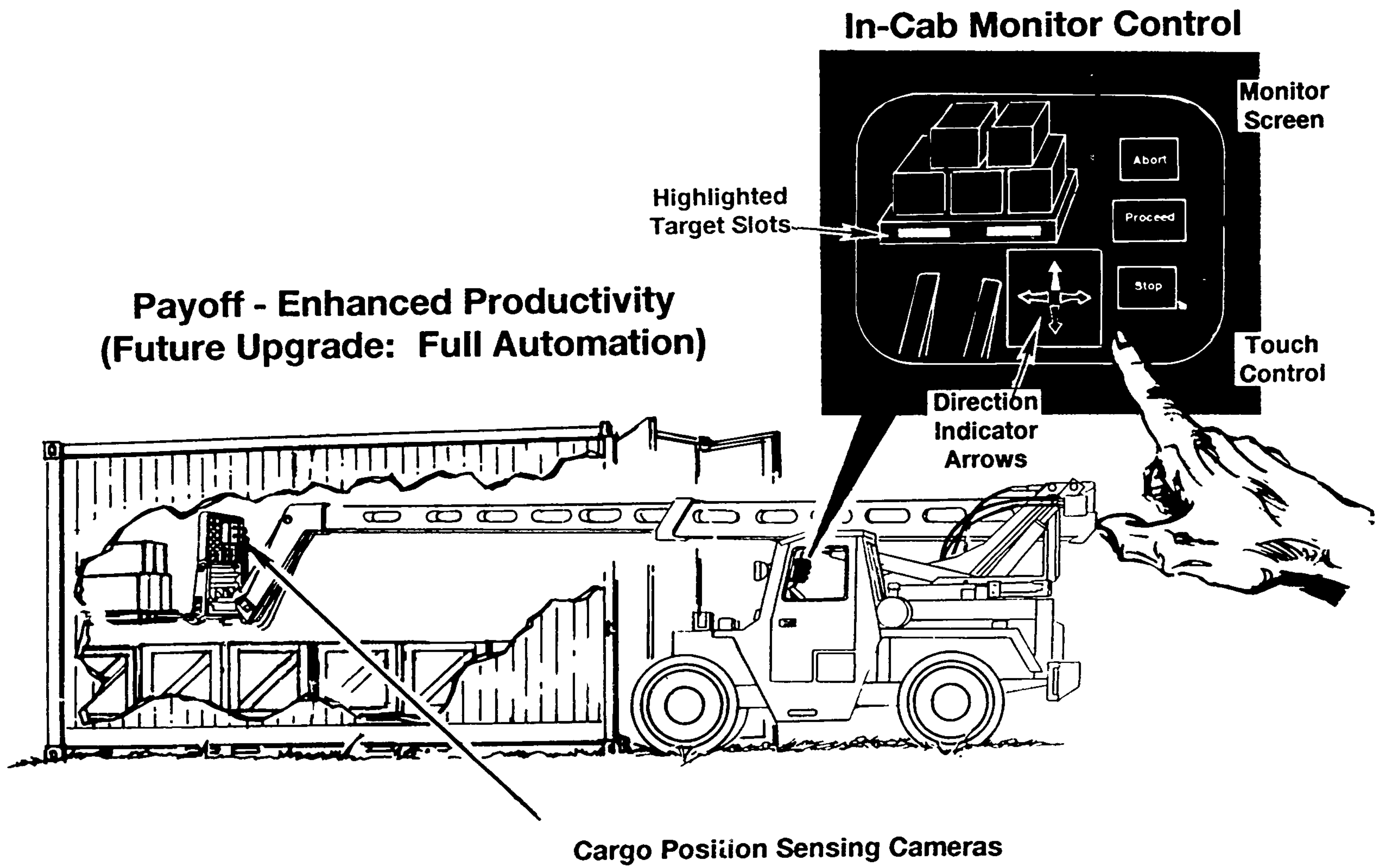


Figure 5. Computer aided load acquisition system.

2. Phase II of CALAS integrates computer technology with the video feedback of the stereoscopic vision system to provide graphic overlays which add to the operators sensory inputs, thereby increasing the accuracy of teleoperative control.

3. Phase III of CALAS involves the integration of the computer of phase II with the equipment controls (i.e., computer linkage with the end-effector position control servovalves).

4. It is important for the operator of a remote vehicle to see the scene in front of the vehicle with a true perspective so navigation around obstacles can be accomplished readily and with certainty. There are two requirements necessary to achieve true perspective from a stereoscopic vision system: (1) the apparent size and distance of objects in front of a vehicle must be the same as perceived by the operator if actually located between the cameras, and (2) the operator must accurately perceive the field of view provided by the camera lenses. These true perspective requirements are readily satisfied in presently available commercial systems.

4.2.3 CALAS Requirements. The stereoscopic vision system for phase I of CALAS, now in procurement, is to be fitted to the NCEL Equipment Controls Test Bed and has the following design requirements.

- The vision system must provide a true perspective video image to the operator with a field of view such that the tips of the ECTB end-effector tines and a 48"x48"x48" object, with it's visible face located at the tips of the tines, be completely visible and in focus.

- The system must be capable of providing either a two-dimensional image or a three-dimensional image, selectable by the operator from within the operator's cab.

- The system must provide easily accessible connections for a standard VCR hook-up for image recording.

- The stereoscopic camera pair shall be housed in a water tight, dust tight, shock resistant container, and mounted on the test bed end-effector back plate.

- Environmentally protected lamps, which provide approximately uniform illumination across the field of view, shall also be mounted on the end-effector back plate.

- The camera and lamp mounts should be positioned such that they do not limit the positioning capabilities of the ECTB boom and end-effector, or limit cargo acquisition/placement capabilities.

- Video image display should be by a high resolution color monitor, equipped with a rigid monitor hood (for glare elimination), and mounted in the operators cab in an easily accessible position clear of all controls.

• The size and position of the monitor should be such that it does not obstruct the operator's view when not in use. All environmental design goals of the electronic systems and components should be in conformance with the guidelines set forth in the Joint SAE/TMC Recommended Environmental Practices For Electronic Equipment Design (Heavy-duty Trucks) - SAE J1455 January 1988.

4.3 Equipment Controls Test Bed

NCEL has awarded a contract for the design, construction, and installation of an Equipment Controls Test Bed (ECTB) to be used as a test platform for the development of HSC, CALAS, and other advanced controls concepts. ECTB delivery is scheduled for the end of November 1990. Figure 6 includes an artist's conception of the ECTB, and outlines its capabilities. The base vehicle is an EBFL manufactured by the LULL Corporation and is similar to the Marine Corp EBFL which is also LULL manufactured.

The control network module incorporated into the ECTB is shown in Figure 7. There are three levels of end-effector controls: (1) master-slave, (2) joystick, and (3) standard lever control. These three levels of control provide the means for comparison studies between those three approaches, and also equip the ECTB with the prevailing methods of heavy equipment end-effector control.

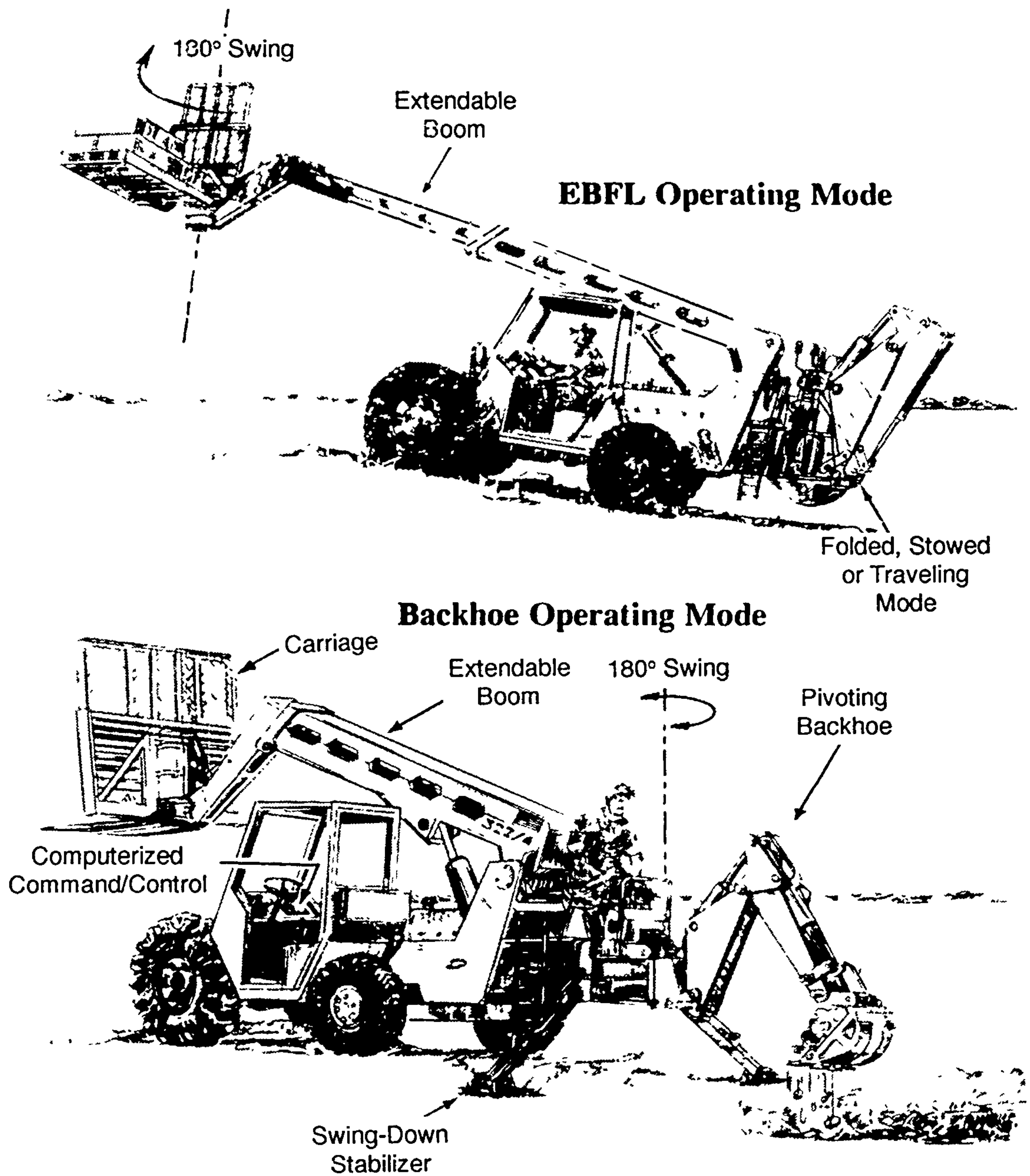
4.3.1. ECTB Status. Modification of the original ECTB contract, contract number N00123-89-C-0239, has been implemented to equip the ECTB with on-board hydraulic power and on-board electrical power. This upgrade will render a completely mobile test facility (total freedom from any external connections). It is this modification that is primarily responsible for the delay in delivery.

4.3.2 Equipment Controls Test Facility. A proposal has been submitted, by project engineering staff in the Advanced MHE/CE Controls program at NCEL, for FY91 ACP funds to furnish the laboratory with an Equipment Controls Test Facility. The ECTB would be the focus of this facility which will involve upgrades to the ECTB as well as supportive test equipment. The proposed facility upgrades are as follows:

1. ECTB hydraulics will be upgraded to include incorporation of additional hydraulics, i.e., electrohydraulic proportional control valves to provide total control system versatility to conduct a variety of tests. The required valves will significantly lower the hydraulic control system sensitivity to hydraulic fluid contamination, thereby considerably improving the ECTB reliability and usefulness as a research facility.

2. Hydraulic/electronic systems diagnostics equipment for instrumentation of the hydraulic control system pressures and temperatures will be added to the facility. Full usefulness as a research facility requires the capability for measurement of these parameters, both static and dynamic.

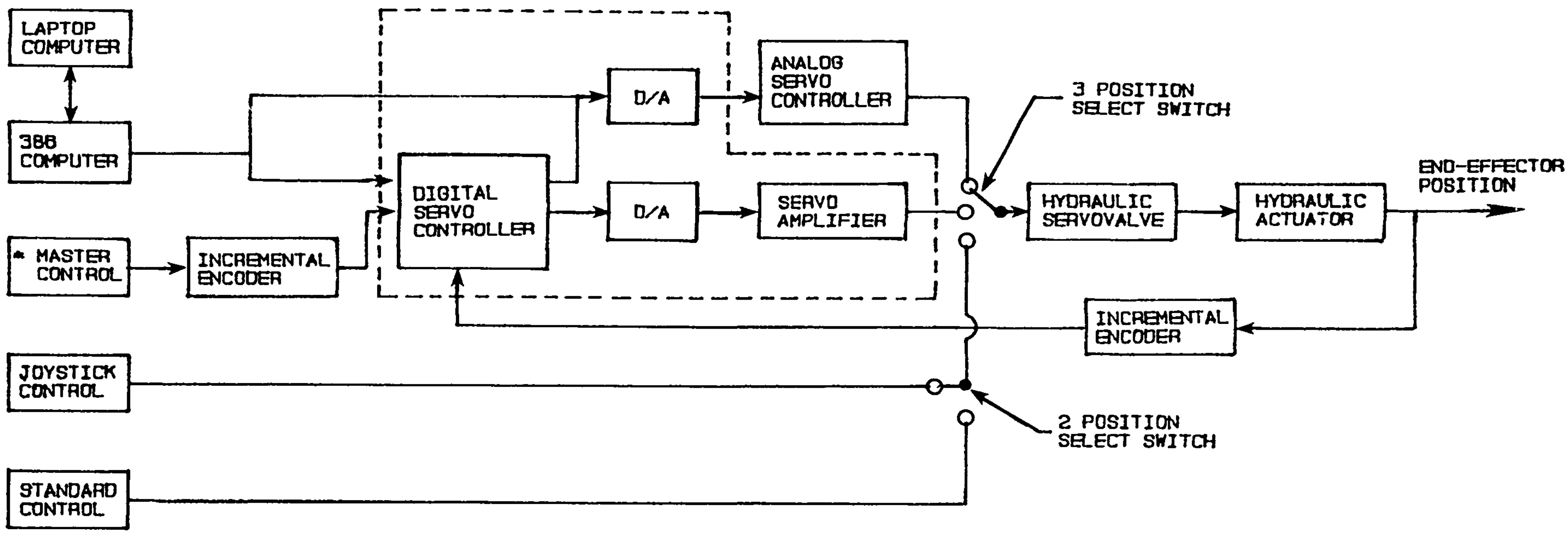
3. Hydraulic/electronic system maintenance/repair equipment peculiar to the ECTB will be added to provide an in-house capability to assure that the ECTB can be satisfactorily maintained and repaired with minimum down time and for minimum cost, when necessary. Maintenance contracts can therefore be avoided.



Capabilities

- 2 Output Devices:
  - Extendable Boom Fork Lift (EBFL) - 5 Axes
  - Backhoe - 4 Axes
- 3 Levels of Input Controls:
  - Conventional Levers
  - Multi-Axis Joysticks
  - Master-Slave Control
- 2 Times Standard Boom Speed Capability
- PC Control
- Analog and Digital Electronic Servo Controllers
- Programmable Position Control System Algorithms
- Position Instrumentation:
  - 2540 Count Optical Incremental Encoders
- Extendable Boom Capability:
  - 2,000 lb Lift at 13 ft Reach (5,000 lb Max)
  - 23 ft 7 in Max Lift Height
- Backhoe Capability:
  - 4,400 lb Max Bucket Dig Force
  - 12 ft 7 in Max Reach
  - 3 cu ft Bucket

Figure 6. NCEL Equipment Controls Test Bed (ECTB).



* For Master-Slave Control

** Components within the dashed line are furnished as a single package

Figure 7. Equipment Controls Test Bed - control network (for a single axis).

4. Enhanced vehicle stabilization (loader outriggers) will be added to the ECTB to provide vehicle stability during rigorous testing that might otherwise upset the vehicle. The alternative would be stationary tie-downs that would negate the ECTB mobility.

5. Supportive test equipment to include steel dummy pallets and cargo simulation weights will be added.

5.0 OTHER EFFORTS IN ADVANCED MHE CONTROLS

Other R&D efforts in advanced controls within government and private industry have been continuously monitored as an ongoing effort to remain abreast of new developments. Through this monitoring, a number of advanced control concepts which may be applicable to Marine Corps MHE (and CE) have been identified. These concepts are outlined below.

5.1 Commercial Activities

To date, a technology surveillance of R&D in advanced MHE controls within private industry has included visits to Caterpillar Inc., John Deere & Co., Carnegie Mellon University, RSI Research Ltd., International Telepresence Corp., Odetics Inc., and Martin Marietta. The work at each of these activities in advanced MHE controls, both ongoing and proposed and which offer potential application to Marine Corp MHE, is outlined below.

Caterpillar Inc., a heavy equipment manufacturer, is pursuing the following areas of technology for adaptation to their heavy equipment design:

- Knowledge based systems for machine diagnostics.
- Dozer controls.
- Self guided vehicles, laser guided and mirrored decals on loads.
- Excavator and backhoe loader control, varying in scope from today's "man on machine" to fully autonomous operation, e.g., multi-axis electronic joysticks, semi-automated linkage controls, force feedback, monitoring systems, teleoperation, auto dig, auto cycles, and autonomous operation.

John Deere & Co., another heavy equipment manufacturer, has been working in telerobotics and the following supporting technologies:

- Data Links/Telemetry
- Controls
- Human Factors Engineering

- Data Acquisition

- Noise/Vibration Engineering

Carnegie Mellon University (CMU) is involved in MHE robotics technology of considerable depth and of wide scope. The following listing of projects at the Field Robotics Center of the Robotics Institute at CMU is suggestive of the depth and scope of MHE Robotics at CMU.

- Autonomous vehicles, e.g., autonomous navigation research.

- Mining automation - locomotion test bed.

- Planetary exploration, e.g., walking robot.

- Automated waste site investigations with mobile robot.

- Robotic excavation for unearthing utility piping.

- Nuclear recovery robots, e.g., Three Mile Island cleanup.

RSI Research LTD., a Canadian company which undertakes system integration projects in the application of automation and robotic technologies, has developed a number of telerobotic technologies in cooperation with the University of British Columbia. Those technologies applicable to MHE controls are:

- Telerobotic conversion of excavator.

- Telerobotic conversion and control of multipurpose Bobcat equipped with stereoscopic vision and robotic manipulator. Resolved motion manipulator (end-effector) control.

- Hall effect joint angle sensors.

- Six degree of freedom, rate controlled joystick.

- Master-Slave control.

- Force feedback.

- Sub-sea robotic manipulator control.

The International Telepresence Corp., (ITC), a Canadian company with expertise in vision systems, is developing systems for the telepresence industry. Telepresence may be defined as the sum total of all information about the worksite that can be transmitted in some form to the remote operator. It is the sense of "presence" as experienced by the operator of a remote work system. The following constitute some of the technology, products and systems developed by ITC for their sponsors:

- Analog and digital vision systems.
- Integrated stereo cameras.
- Remote image alignment using electronic methods.
- Remote image convergence using both electronic and mechanical methods.
- Remote camera switching.
- Multiplexing full bandwidth video signals over one coaxial cable.
- Real-time and off-line image enhancement software.
- Headtracker systems.
- High speed pan and tilt camera units.
- Two-monitor head-mounted displays.

Odetics Inc., located in Anaheim, CA, has a number of proposed and ongoing DOD efforts of interest, these include:

- Proposals to provide support for U.S. Army telerobotic MHE program (Belvoir Research, Development and Engineering Center (BRDEC), Virginia).
- Proposal for development of a load sensing/acquisition system for U.S. Air Force MHE to move ordnance (Air Force Engineering and Services Center (AFESC), Tyndall AFB, Florida).
- Contract to automate several excavator functions to support the U.S. Air Force Rapid Runway Repair (RRR) project (AFESC, Tyndall AFB, Florida).
- Contract for a 155 mm artillery shell and packaged charge autoloader for the U.S. Army M-109 tank (Picatinny Arsenal, New Jersey).
- Electro-optical, infrared, laser-based scanners for application to military MHE and CE.

Martin Marietta, a large defense contractor working closely with the U.S. Army Human Engineering Laboratory (HEL) on the Field Material Handling Robot (FMR), is trying to market a Pallet Acquisition Sensor System (PASS). PASS is basically a position detection network, relying on horizontally pointing ultrasonic sensors for distance information and on vertically pointing infrared sensors for edge detection.

5.2 Government Activities

Government activities identified for having projects dealing in advanced controls technology for MHE and CE include the following: (1) U.S. Army Human Engineering Laboratory (HEL), Aberdeen Proving Ground, Maryland; (2) U.S. Army Belvoir RD&E Center (BRDEC), Fort Belvoir, Virginia; (3) Air Force Engineering and Services Center (AFESC), Tyndall AFB, Florida; (4) National Institute of Standards and Testing (NIST), Gaithersburg, Maryland. Efforts by these activities in advanced MHE/CE controls technology are discussed below.

The staff of the Robotics Technology Base Group (RTBG) at the U.S. Army Human Engineering Laboratory (HEL), have briefed NCEL engineers on the mission and activities of this group. The most significant ongoing R&D (6.2) project at HEL of interest and potential application to Marine Corps needs is the Field Material Handling Robot (FMR), depicted conceptually in Figure 8. Development of the FMR has included efforts by Martin Marietta and NIST. The FMR is designed to operate as stationary MHE for automated rapid unloading of palletized material from flat-bed trucks or other unenclosed delivery vehicles. The FMR is designed to be controlled either manually or remotely. In addition to the FMR, HEL's Robotics Program has been looking at a concept for automating vehicle navigation, called "Retrotraverse". The retrotraverse capability would enable autonomous reverse traverse of a vehicle over the path already established for the forward traverse, a potentially valuable capability in a hostile environment.

The staff of the Rough Terrain MHE Team at the U.S. Army Belvoir Research, Development and Engineering Center (BRDEC), have briefed NCEL engineers on the All Terrain Lifter Articulated System (ATLAS), an ongoing R&D project at BRDEC. The ATLAS, depicted conceptually in Figure 9, is a mobile, rough terrain, material handling vehicle developed by FMC Corp., Minneapolis, Minn., for BRDEC. The base vehicle of the ATLAS is identical to the Marine Corp EBFL presently on order (same manufacturer). Utilizing state-of-the-art sensor technology and microprocessor controls, the mission of the ATLAS is to provide lift capabilities required for future Combat Service Support Operations. The ATLAS is designed to operate on rough terrain, over the road, in NBC contaminated areas, and in extreme climate regions. The characteristics and status of the ATLAS are as follows:

Characteristics:

- Top speed of 45 miles per hour.

- Lift capacity of up to 10,000 pound load.

- Up to 21.5 feet reach with 4,000 pound load.

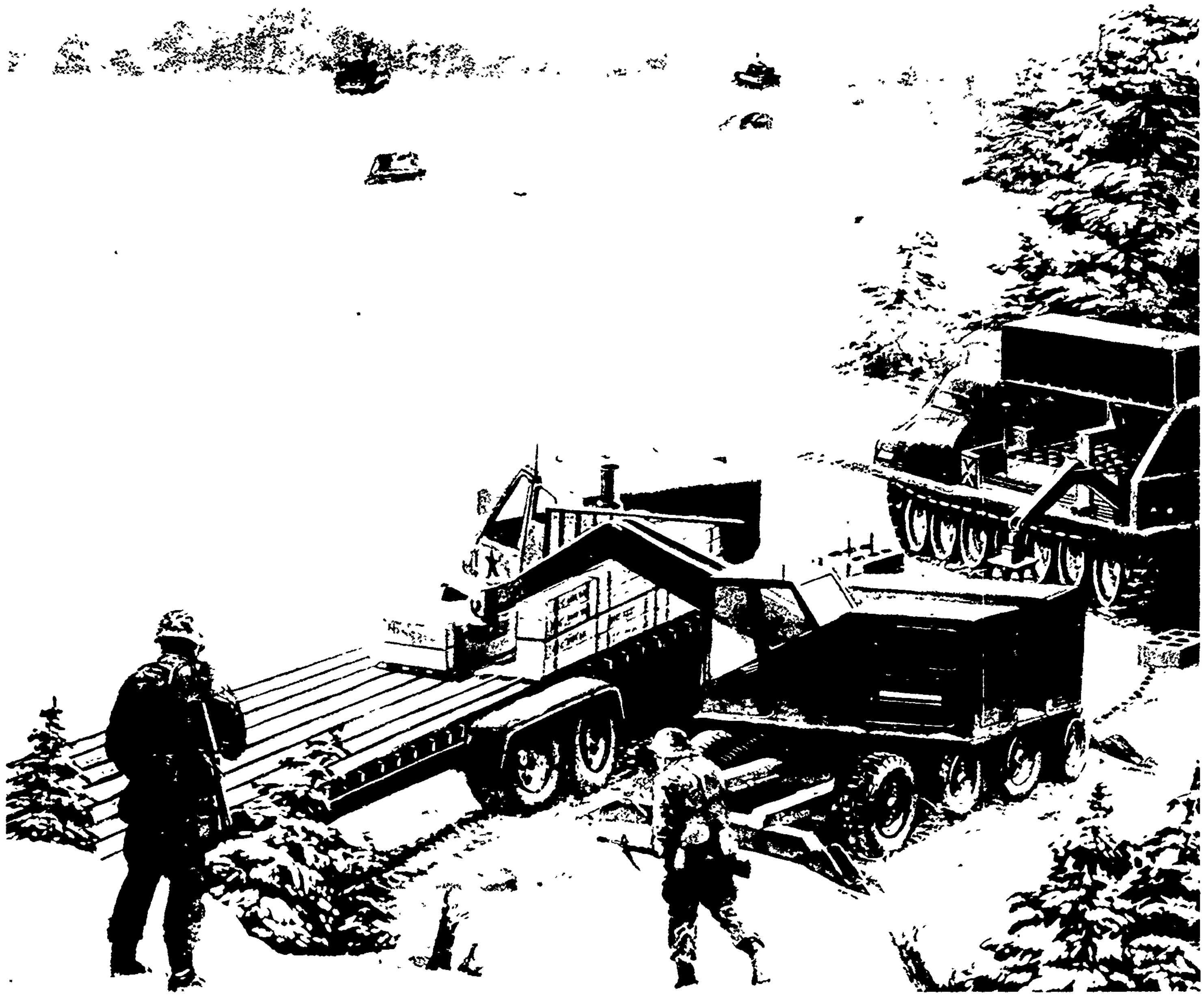


Figure 8. U.S. Army Field Material Handling Robot (FMR).

U.S. Army Belvoir RDT&E Center

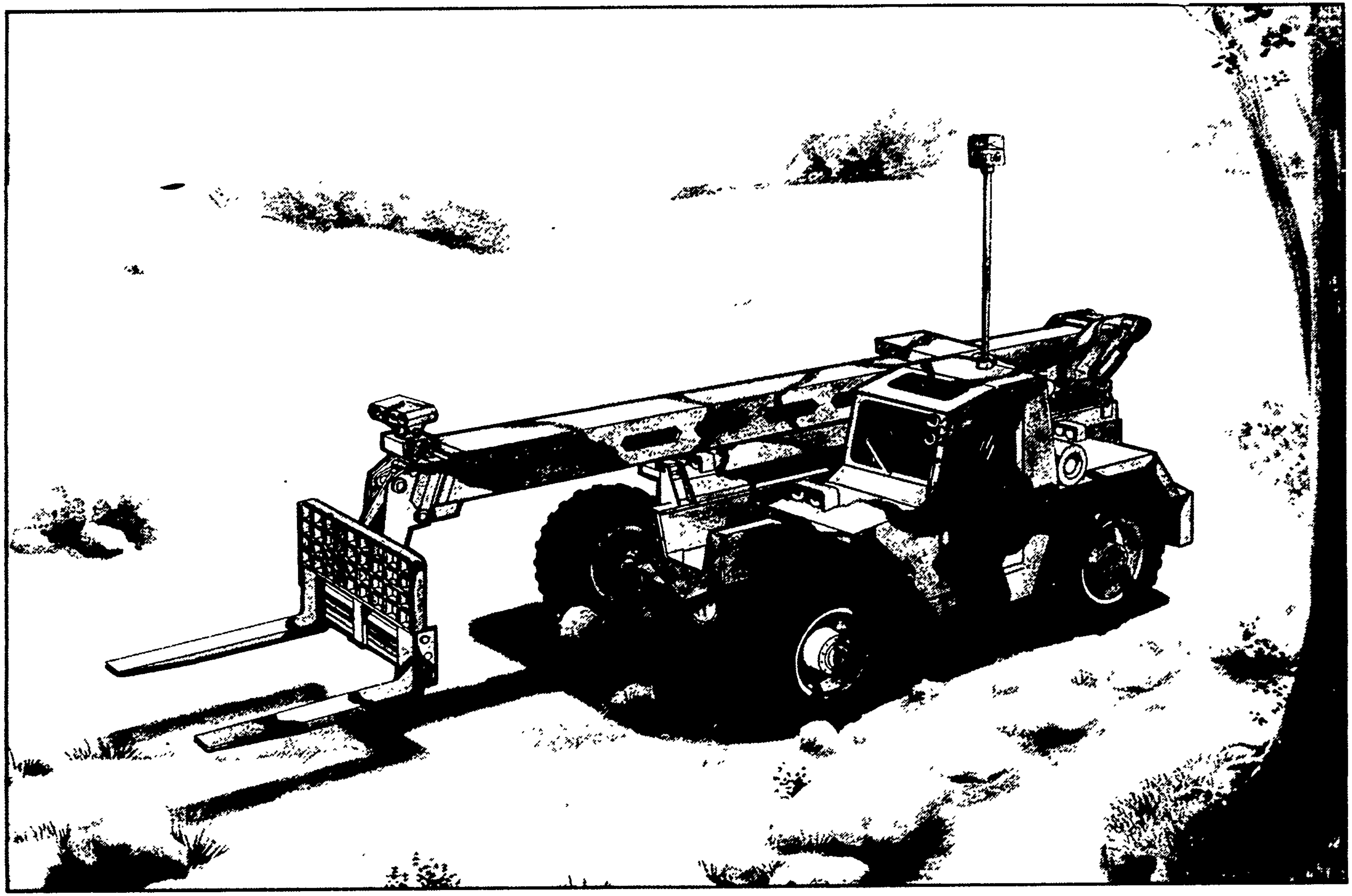


Figure 9. U.S. Army All-Terrain Lifter Articulated System (ATLAS).

- 60 inch seawater fording depth.
- Micro-climate cooled cab for NBC operations.
- C-130 air transportable.
- Computer-coordinated boom control for precise vertical and horizontal fork movement.
- Chemical agent detection and alarm capability.

Status:

- Developmental prototype received by BRDEC July 1989.
- Prototype undergoing testing at U.S. Army Proving Ground. Scheduled completion: October 1990.
- Oak Ridge National Laboratory (ORNL) under contract to develop computer-coordinated boom control and cargo handling stability control.

The U.S. Air Force Engineering and Services Center (AFESC) has been pursuing the modification of a John Deere Model 690C Multipurpose Excavator to improve its operational capabilities and productivity through easier operation, and reduced operator skill and training requirements. This effort is a part of the U.S. Air Force Rapid Runway Repair (RRR) System, an ongoing project at AFESC, and offers potential for future upgrades to teleoperative control as well as fully autonomous control. Through this effort a number of advanced control concepts applicable to Marine Corp MHE/CE controls have been developed, these include:

- Multi-function joystick design.
- Computer-based, multi-function joystick control system.
- Master-Slave control.
- Supporting electrical/electronic systems design.
- Excavator hydraulic system redesign and modification.
- Operator training simulator.
- Pre-programmed excavator functions (automation).
- Sensor technology.

The National Institute of Standards and Testing (NIST) has developed and demonstrated a hierarchically-structured real-time control system (RCS) for application to intelligent robotic systems. RCS uses sensory feedback to assess the state of the environment and, based on this assessment, makes control decisions in real time, e.g., determining the next task to be executed, or where to move the robotic system relative to other objects in the work area, etc. More specifically, NIST has developed an RCS and fork-mounted sensor system which is being used on the U.S. Army FMR. This package allows the FMR to perform ammunition pallet acquisition and transfer in a totally autonomous mode.

6.0 CONCLUSIONS AND RECOMMENDATIONS

1. Through the research of this exploratory development effort in Advanced MHE Controls, considerable insight has been gained into the direction to be taken for future efforts in advanced MHE/CE controls. Advances in sensor technology, computer technology, communications, instrumentation, servocontrollers, and image processing are pushing heavy equipment controls towards teleoperation (remote control with man in the control loop) and full automation (man removed from the control loop). It is recommended that future exploratory development efforts in controls technology contribute in some manner to the development of both teleoperation and full automation.

2. A logical step in the development of teleoperation and automation is to first provide the on-board operator with feedback information (e.g., video feedback, audio feedback, force feedback, computer generated graphical images, etc.) which can be used to enhance the operators ability to accomplish the task at hand. Once this has been accomplished, system designs to relocate the operator to a remote location may be addressed.

3. The feasibility of the original concept of applying commercially available state-of-the-art electronic servo-controllers to MHE end-effector position control systems in order to achieve high speed control, as described in Section 4.1 of this report, has been demonstrated through computer model simulation.

4. Little is known about the relative merits of the various electronic servo-controllers available. Any future effort on application of these controllers to USMC fielded MHE or CE should incorporate, as one objective, the evaluation of alternative controllers.

5. For any one electronic servo-controller, not enough is known about the relative merits of the various algorithms which it offers, i.e., which algorithms are better suited to what applications. Similarly, the procedure for sizing the algorithm coefficients for optimum performance is poorly structured since there are no guidelines for doing this (electronic servo-controllers are so new that none have been developed). The development of such application guidelines is important if this technology is to be exploited in the future.

6. The HSC application investigated in this task, i.e., EBFL boom translation position control is a good application for demonstrating initial proof of concept. However, applications offering greater benefit are probably in the area of earth-moving equipment, especially excavators and backhoes. This is because of the high stiffness of the load in the case of the EBFL application, whereas load stiffness for excavators and backhoes is relatively low (in the yaw mode), thereby constituting a more difficult control problem.

7. Further effort on High Speed Control should be integrated with development of master-slave control, particularly for any application to excavators or backhoes, in order to realize optimum overall system performance. The shortfall of this recommendation is that a properly designed master-slave control would include force-feel feedback, a technology which is not yet state-of-the-art.

8. The use of sophisticated and expensive electrohydraulic servovalves, incorporated into the Equipment Controls Test Bed, appears to represent an over-design with respect to High Speed Control. Electrically piloted proportional hydraulic spool valves, although not nearly as responsive as servovalves, seem to be fast enough to implement the concept. Also, they are much less sensitive to hydraulic fluid contamination.

9. In the area of palletized cargo acquisition from ISO containers, there is a real need for enhancement of the operator's performance so as to improve safety and productivity. The first step toward such a goal is to provide the operator with an in-cab 3-D video image of the target cargo and his forks. Subsequent steps should include computer-aided acquisition and automated cargo acquisition. Safety will be improved through elimination of the spotter presently needed inside ISO containers.

10. The technology required for implementation of enhanced and computer-aided acquisition and automated cargo acquisition is commercially available.

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Appendix A

DERIVATION OF TRANSFER FUNCTIONS
FOR
EXTENDABLE BOOM POSITION CONTROL SYSTEM
ON
NCEL EQUIPMENT CONTROLS TEST BED

NOMENCLATURE

A = net area of piston

C_{LR} = ram leakage coefficient = q_b/P_L

M = actuator piston, boom and load mass

P_s = supply pressure

P_L = load pressure

P_R = return pressure

ΔP_v = pressure drop across valve

q_v = perturbations in valve flow rate

q_L = perturbations in load flow rate

q_p = perturbations in flow rate due to piston displacement

q_b = leakage flow past piston

q_c = flow associated with fluid compressibility

q_h = flow associated with hose compliance

Q = valve flow rate

s = Laplace operator

g = gravitational constant

t = time

F = actuator cylinder force

V = fluid volume under compression

X = valve spool displacement

x = perturbations in valve spool displacement

y = actuator piston/load displacement

β = bulk modulus of fluid

ξ = damping ratio

ω_n = natural frequency of actuator, boom and load system

K_v = servovalve discharge coefficient = $(Q/X) \;\; 2/\Delta P_v$

EXTENDABLE BOOM POSITION CONTROL SYSTEM SPECIFICATIONS
(Boom Translation Mode)

No. of actuators	2
Lull Eng'g part no.	P27750
Bore diameter	3.002 - 3.006 in
Piston diameter	2.985 - 2.987 in
Piston land length	3.00 ± 0.030 in
Piston rod diameter	1.999 ± 0.001 in
Piston rod length	131.19 ± 0.030 in
Stroke	106 in
Actuator creep due to ram leakage	3.33×10^{-5} in/min

2. **Hydraulic Fluid**

Bulk modulus (β)	200,000 psi

3. **Hydraulic Lines**

Extension line:	
Length	158 in
Inside diameter	0.62 in
Retraction line:	
Length	164 in
Inside diameter	0.62 in
Material	synthetic rubber, steel mesh reinforced

4. **Weight (W) of actuator/load dynamic mass**

Assumed	$500 \text{ lb} < W < 5000 \text{ lb}$

5. **HPU Supply Pressure, P_s**

Pressure	3,000 psi

6. **Load Pressure, P_L**

Assumed $(P_L)_{av}$	1,000 psi

7. **Analog Electronic Servo-controller**

Moog model 121-132 controller:
Proportional, integral, lag-lead, derivative-lag or PDF (Psuedo-Derivative Feedback) control.

8. **Digital Electronic Servo-Controller**

Delta-Tau Data Systems, Inc. two-axis SMCC (Smart Motion Control Card)

9. **Electrohydraulic Servovalve**

Moog model 72-103 servovalve
Maximum rated flow at 3000 psi . . . . 94 gal/min

SUMMARY OF CALCULATED COEFFICIENTS

Servovalve:

$k_{sv} = 13.9$ in^3/sec/ma (p. A-12)

$2\xi_v/\omega_{nv} = 0.00557$ sec (p. A-13)

$1/(\omega_{nv})^2 = 1.58 \times 10^{-5}$ sec^2 (p. A-13)

$\tau_{sv} = 0.0183$ sec*

Actuator/Load

$k_L = k_a k_{ee} = 0.127$ in^{-2} (p. A-9)

$0.0231 \text{ sec} < 2\xi_a/\omega_{na}) < 0.231$ sec (p. A-12)

$1.56 \times 10^{-4} \text{ sec}^2 < 1/(\omega_{na})^2 < 1.60 \times 10^{-3} \text{ sec}^2$ (p. A-9: ω_{na})

Encoder, Boom Translation**

$k_e = 0.0943$ volts/in; resolution = 0.006 inch

*Calculated from Moog servo-valve data provided by Moog, Inc.
**Data from manufacturer, Advanced Systems Concepts, Inc., Altadena, CA.

EBFL BOOM (TRANSLATION) POSITION CONTROL SYSTEM

Derivation of Hydraulic Actuator Transfer Function

Force Developed by the Actuator (Cylinder)

$$F = A\,\Delta P = A(P_L - P_R)$$

So,

$$F(s) = A\,P_L(s) \tag{1}$$

since P_R is a constant.

For a purely inertial load, the actuator force,

$$F = M\frac{d^2y}{dt^2} \quad or \quad F(s) = M s^2 y(s) \tag{2}$$

Combining equations (1) and (2):

$$A P_L(s) = M s^2 y(s) \tag{3}$$

Flow through the servovalve,

$$Q = K_v X \sqrt{\Delta P_v / 2} \tag{4}$$

Differentiating,

$$dQ = \frac{\partial Q}{\partial X} dX + \frac{\partial Q}{\partial(\Delta P_v)} d(\Delta P_v) \tag{5}$$

Now,

$$\Delta P_v = P_s - P_L$$

where P_s is a constant. So,

$$d(\Delta P_v) = -dP_L$$

Substituting in equation (5):

$$dQ = \frac{\partial Q}{\partial X} dX - \frac{\partial Q}{\partial P_L} dP_L \tag{6}$$

For small changes in the variables,

$$dQ = q_v \,; \quad dX = x \,; \quad dP_L = p_L$$

So, we rewrite equation (5) as:

$$q_v = \left(\frac{\partial Q}{\partial X}\right) x - \left(\frac{\partial Q}{\partial P_L}\right) p_L \tag{7}$$

Now, from equation (4):

$$\frac{\partial Q}{\partial X} = K_v \sqrt{\Delta P_v / 2} \tag{8}$$

$$\frac{\partial Q}{\partial P_L} = \frac{K_v}{\sqrt{8\,\Delta P_v}} X \tag{9}$$

The expressions for $(\partial Q/\partial x)$ and $(\partial Q/\partial P_L)$ are regarded as constants at some steady-state operating point.

Hydraulic Cylinder Flow

Flow to the cylinder, q_L, is defined as:

$$q_L = q_v = q_P + q_b + q_c \tag{10}$$

where:

$$q_p = A \frac{dy}{dt} \qquad so \quad q_P(s) = Asy(s) \tag{11}$$

$$q_b = C_{LR} P_L \qquad so \quad q_b(s) = C_{LR} P_L(s) \tag{12}$$

$$q_c = \frac{V}{\beta} \frac{dP_L}{dt} \qquad so \quad q_c(s) = \frac{V}{\beta} s P_L(s) \tag{13}$$

neglecting compliance and transport lag of hoses.

Substituting equations (11), (12), and (13) into equation (10):

$$q_L(s) = A s y(s) + C_{LR} P_L(s) + \frac{V}{\beta} s P_L(s) \tag{14}$$

small changes in servovalve flow to small changes in flow to cylinder, we combine equations (7) and (14):

$$\left(\frac{\partial Q}{\partial X}\right) x(s) - \left(\frac{\partial Q}{\partial P_L}\right) P_L(s) = Asy(s) + C_{LR} P_L(s) + \frac{V}{\beta} s P_L(s)$$

Dropping the function indicator "(s)" and substituting for P_L from equation (3):

$$\left(\frac{\partial Q}{\partial X}\right) x - \left(\frac{\partial Q}{\partial P_L}\right) \frac{M}{A} s^2 y = Asy + C_{LR}\left(\frac{M}{A}\right) s^2 y + \frac{V}{\beta}\,\frac{M}{A} s^3 y$$

Grouping terms:

$$\left(\frac{\partial Q}{\partial X}\right) x = sy\left[\left(\frac{V}{\beta}\,\frac{M}{A}\right) s^2 + \frac{M}{A}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right) s + A\right] \tag{15}$$

Units check:

$$\frac{in^3}{sec} = \frac{in}{sec}\left[\left(\frac{in^3\, in^2}{lb}\,\frac{lb\ sec^2}{in\ in^2}\right)\frac{1}{sec^2} + \frac{lb\ sec^2}{in\ in^2}\left(\frac{in^3}{sec}\,\frac{in^2}{lb}\right)\frac{1}{sec} + in^2\right] = \frac{in^3}{sec}$$

Rewriting equation (15):

$$\frac{y}{x} = \frac{(\partial Q/\partial X)/A}{s\left[\left(\frac{V}{\beta}\,\frac{M}{A^2}\right) s^2 + \frac{M}{A^2}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right) s + 1\right]} \tag{16}$$

Now,

$$\frac{y(s)}{Q(s)} = \frac{y(s)/x(s)}{\partial Q/\partial X}$$

since $\partial Q/\partial X$ is taken at the operating point for x.

Therefore,

$$\frac{y(s)}{Q(s)} = \frac{1/A}{s\left[\dfrac{s^2}{\beta A^2/VM} + \dfrac{M}{A^2}\left(C_{LR} + \dfrac{\partial Q}{\partial P_L}\right)s + 1\right]} \tag{17}$$

Equation (17) is in the form,

$$\frac{y(s)}{Q(s)} = \frac{k_L}{s\left(\dfrac{s^2}{\omega_n^2} + \dfrac{2\,\xi}{\omega_n}\,s + 1\right)} \tag{18}$$

Therefore,

$$\omega_{na} = A\sqrt{\beta/VM} \tag{19}$$

and

$$\frac{2\,\xi_a}{\omega_{na}} = \frac{M}{A^2}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right)$$

So,

$$\xi_a = \frac{M}{2A^2}\left(A\sqrt{\beta/VM}\right)\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right)$$

or,

$$\xi_a = \frac{1}{2A}\sqrt{\frac{\beta M}{V}}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right) \tag{20}$$

and

$$k_L = 1/A \tag{21}$$

Evaluation of Coefficients in the System Transfer Functions

Consider the transfer function, y(s)/Q(s), for the actuators and load:

Equation (18):

$$\frac{y(s)}{Q(s)} = \frac{k_L}{s\left(\frac{s^2}{\omega_{na}^2} + \frac{2\,\xi_a}{\omega_{na}} s + 1\right)}$$

Equation (21):

$$k_L = 1/A; \qquad A = 7.86\ in^2*$$

So

$$k_L = 0.127\ in^{-2} \tag{22}$$

Equation (19):

$$\omega_{na} = A\sqrt{\beta / VM}$$

where: β = 200,000 psi

V = (π/4)(9 in^2) x 106 in x 2* = 1,498 in^3

500 lb < M g < 5000 lb, (g = 32.2 ft/sec^2)

or 15 lb sec^2/ft < M < 150 lb sec^2/ft

So,

$$\omega_{na} = 7.86\ in^2 \sqrt{\frac{200{,}000\ lb}{in^2\,(1{,}498\ in^3)\,M}}$$

$$= \sqrt{\frac{8{,}248\ lb}{in\ M}}$$

Now, 1.3 lb sec^2/in < M < 13 lb sec^2/in. Therefore,

$$25\ sec^{-1} < \omega_{na} < 80\ sec^{-1} \tag{23}$$

---

*Note: Since there are two actuators, A and V are doubled.

Equations (19) and (20):

$$\frac{2\,\xi_a}{\omega_{na}^2} = \frac{M}{A^2}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right) \tag{24}$$

From Moog Series 72 Servovalve Data Sheet:

$$\begin{aligned}\frac{\partial Q}{\partial P_L} &= 0.021\ gpm/psi\ x\ 2.228\ x\ 10^{-3}\ \frac{ft^3/sec}{gpm} \\ &= 0.021\ (2.228\ x\ 10^{-3})\ 1728(12)\ \frac{ft^3\ in^3}{sec\ (psi)\ ft^3}\end{aligned} \tag{25}$$

Therefore,

$$\frac{\partial Q}{\partial P_L} = 0.97\ in^3/psi\text{-sec}$$

Determine C_{LR}:

Equation (12):

$$C_{LR} = q_b / P_L = \partial q_b / \partial P_L$$

Now,

$$q_b = C_o A_o \sqrt{\frac{2g}{\rho}\,(P_s - P_L)}$$

where:

C_o = flow coefficient for the annular orifice formed by piston and cylinder bore

A_o = cross-sectional area of orifice

ρ = fluid density

$$\frac{\partial q_b}{\partial P_L} = C_o A_o \sqrt{\frac{2g}{\rho}}\left(\frac{1}{2}\right)\sqrt{\frac{1}{\bar{P}_L}}$$

Therefore,

$$C_{LR} = C_o A_o \sqrt{\frac{g}{2 \rho \bar{P}_L}} \tag{26}$$

From *Crane Technical Paper 410*, page A-19:

$$C_o = 0.60$$

A_o is the annulus formed by:

a) a 3.004-inch average diameter
b) a 2.986-inch average diameter

Therefore, $A_o = \pi$ (2.995 inches) 0.009 inches. So,

$$A_o = 0.0847 \; in^2$$

From *Crane Technical Paper 410*, page A-7, select:

$$\rho(average) = 52 \; lb/ft^3$$

Assume:

$$\bar{P}_L = 1000 \; psi$$

Equation (26):

$$C_{LR} = 0.60(0.0847 \; in^2) \sqrt{\frac{32.2 \; ft \; (ft^3) \; in^2 (144)(144) \; in^4}{sec^2 (2) \, 52 \; lb \, (1000 \; lb) \, ft^4}}$$

$$C_{LR} = 0.13 \; in^3/psi\text{-sec}$$

Equation (24):

$$\frac{2 \, \xi_a}{\omega_{na}} = \frac{M}{A^2} \left(C_{LR} + \frac{\partial Q}{\partial P_L} \right)$$

Substituting constants:

$$\frac{2 \, \xi_a}{\omega_{na}} = \frac{M}{61.8 \; in^4} (0.13 + 0.97) \; \frac{in^3/sec}{psi}$$

or,

$$\frac{2\,\xi_a}{\omega_{na}} = \frac{0.0178}{in^4}\;\frac{in^3/sec}{lb/in^2}\;M\left(\frac{lb-sec^2}{in}\right)$$

$$= 0.0178\;\frac{in^3\,(in^2)}{in^4\,(lb)\,sec}\;M\left(\frac{lb-sec^2}{in}\right)$$

$$= 0.0178\;M\;sec$$

where M is in lb-sec^2/in. Therefore,

$$0.0231\;sec \;<\; \frac{2\,\xi_a}{\omega_{na}} \;<\; 0.231\;sec \tag{27}$$

Equation (23):

$$25\;sec^{-1} \;<\; \omega_{na} \;<\; 80\;sec^{-1}$$

Therefore:

$$1.56 \times 10^{-4}\;sec^2 \;<\; \frac{1}{\omega_{na}^2} \;<\; 1.60 \times 10^{-3}\;sec^2 \tag{28}$$

Consider the transfer function, Q(s)/i(s), for the servovalve:

From the system block diagram:

$$\frac{Q(s)}{i(s)} = \frac{k_{sv}}{1 + \left(\frac{2\,\xi_v}{\omega_{nv}}\right)s + \left(\frac{1}{\omega_{nv}^2}\right)s^2} \tag{29}$$

Specifically, the Moog series 72 servovalve is addressed.

From *Moog Series 72 Servovalve Data Sheet*:

$$k_{sv} = \frac{60\ gpm\ (2.228) \times 10^{-3}\ ft^3/sec\ (1728)\ 12\ in^3}{200\ ma\ gpm\ ft^3}$$

$$k_{sv} = 13.9\ \frac{in^3/sec}{ma}$$

From the Moog Sereis 72 Servovalve Data Sheet, and substantiated by Moog Applications Engineer, Marcus Kihlberg:

$$\omega_{na} = 40\ cps = 251\ sec^{-1}$$

$$\xi_v = 0.7$$

So,

$$\frac{2\ \xi_v}{\omega_{nv}} = 0.00557\ sec$$

and

$$\frac{1}{\omega_{nv}^2} = 1.58 \times 10^{-5}\ sec^2$$

If K_e = encoder gain, and assuming SMCC full input range/full actuator stroke, then:

$$k_e = \frac{10\ volts}{106\ in}$$

or

$$k_e = 0.09433\ volts/in$$

Hydraulic Hose Compliance

To account for hydraulic hose compliance, the following data was obtained from *Lull Engineering Corp.* and *Parker Aircraft Co.**

Hose identification .... Parker 431 series synthetic rubber/steel mesh-reinforced hydraulic-hose
Length .... 158 inches and 164 inches
Outside diameter .... 15/16 inch
Inside diameter .... 5/8 inch

Volumetric expansion .... 2.0 cc/ft @ 1,800 psi (P_L)
....
2.5 cc/ft @ 2,750 psi (P_L)
....
(linear for P_L > 500 psi)

In equation (1), we add the term:

$$q_h = \frac{dV_h}{dt}$$

so that

$$q_L = q_p + q_b + q_c + q_h = q_v \tag{30}$$

Now

$$\Delta V_h = k_h \Delta P_L$$

So,

$$\frac{dV_h}{dt} = q_h = k_h \frac{dP_L}{dt}$$

and

$$q_h(s) = k_h s P_L(s) \tag{31}$$

Adding in the q_h term revises equation (14) to read:

$$q_L(s) = A s y(s) + C_{LR} P_L(s) + \left(\frac{V}{\beta} + k_h\right) s P_L(s) \tag{32}$$

*Data Source: Parker Aircraft Co., Technical Service Center, Hose Service Division, Wickliffe, Ohio 44092, (216) 943-5000.

Without the q_h term, equation (14) reads:

$$q_L(s) = A\,s\,y(s) + C_{LR} P_L(s) + \frac{V}{\beta} s\,P_L(s)$$

Therefore, the addition of the q_h term (hose compliance) merely requires the substitution of

$$\left(\frac{V}{\beta} + k_h\right)$$

or

$$\frac{1}{\beta}\,(V + k_h\,\beta)$$

for V/β in equations (15) through (20).

Or substitute $(V + k_h\beta)$ for V in equations (15) through (20). Hence, equation (19) becomes:

$$\omega_n = A\sqrt{\beta/(V + k_h\,\beta)M} \qquad (33)$$

and equation (20) becomes:

$$\xi = \frac{1}{2A}\sqrt{\frac{\beta M}{V + k_h\,\beta}}\left(C_{LR} + \frac{\partial Q}{\partial P_L}\right) \qquad (34)$$

Re-evaluation of Coefficients in the System Transfer Function

From the Parker data,

$$k_h = \frac{\Delta V_h}{\Delta P_L} = \frac{2.5\ cc/ft\ -\ 2.0\ cc/ft}{2750\ psi\ -\ 1800\ psi}\,L_h(eff.)$$

where L_h(eff.) = effective hose length. Conservatively,

$$L_h(eff.) = 0.9\ x\ \text{actual hose length}\ L_h$$

or

$$L_h(eff.) = 0.9(164\ in)\,\frac{ft}{12\ in} = 12.3\ ft$$

Therefore,

$$k_h = \frac{0.5\ cc/ft}{950\ psi} \times 12.3\ ft \times \frac{0.0610\ in^3}{cc}$$

So

$$k_h = 4.0 \times 10^{-4}\ in^3/psi$$

and

$$k_h\,\beta = 4.0 \times 10^{-4}\ \frac{in^3}{psi} \times 200{,}000\ psi$$

or

$$k_h\,\beta = 80\ in^3$$

The term $k_h\beta$ is to be added to V in re-evaluation of coefficients; since $V = 1{,}498\ in^3$ and $k_h\beta = 80\ in^3$, it is clear that the correction is in the neighborhood of 5%. Such a correction is small enough to be ignored. Hence, the coefficients will be left unrevised.

Appendix B

HSC COMPUTER SIMULATION RESULTS

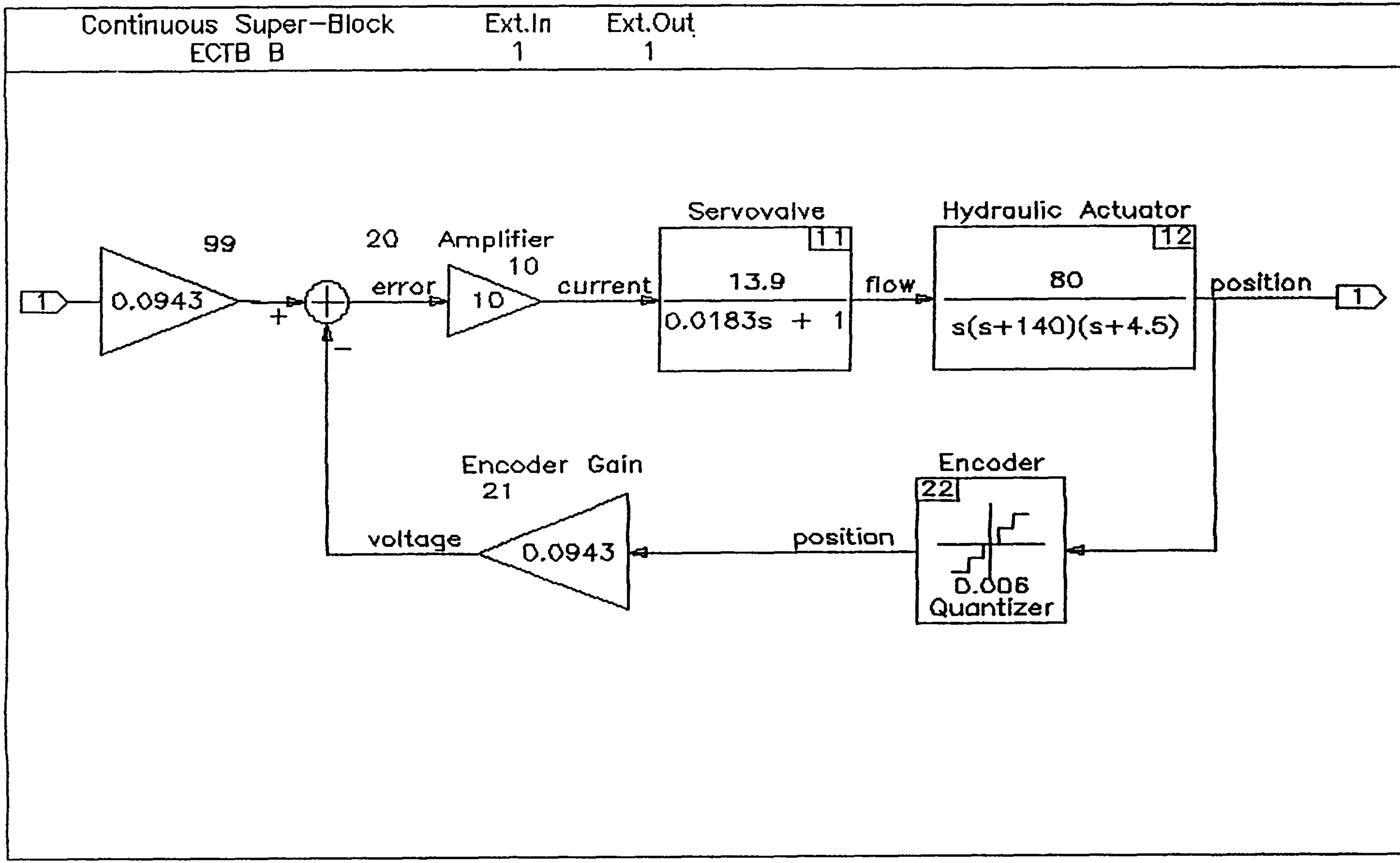

Figure B-1. Baseline Control System block diagram.

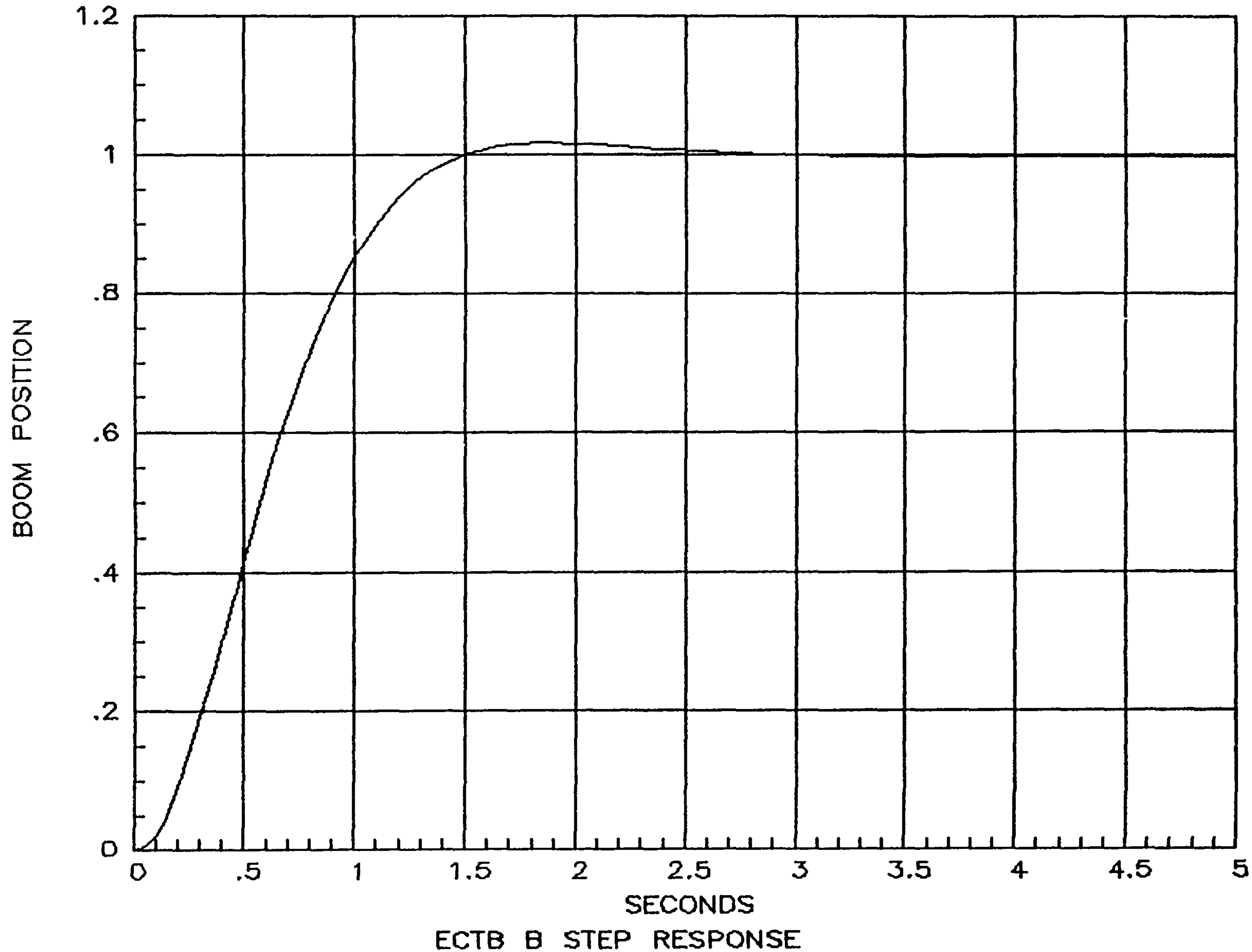

Figure B-2. Baseline Control System response.

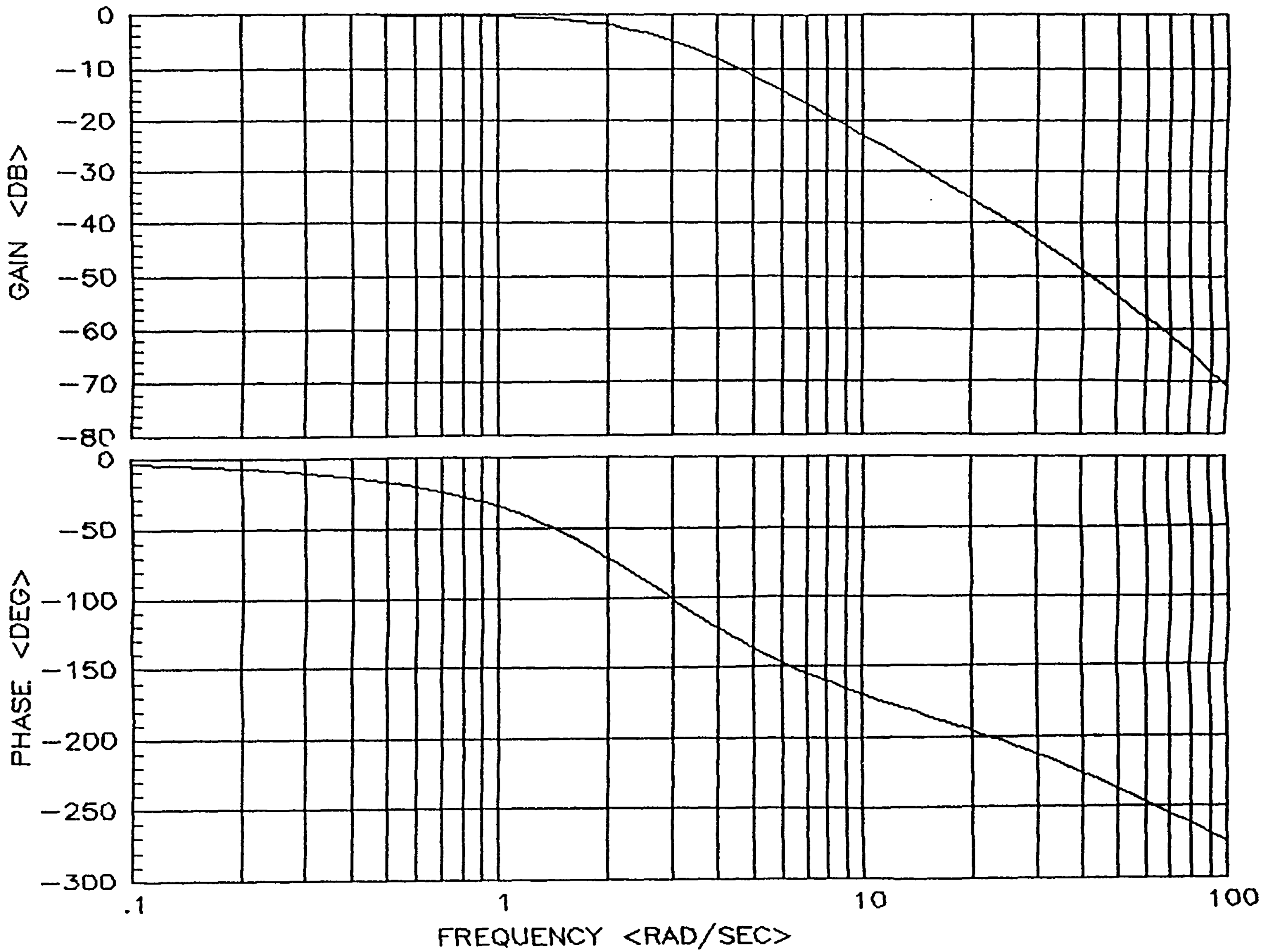

Figure B-3. Closed loop frequency response - Baseline Control System.

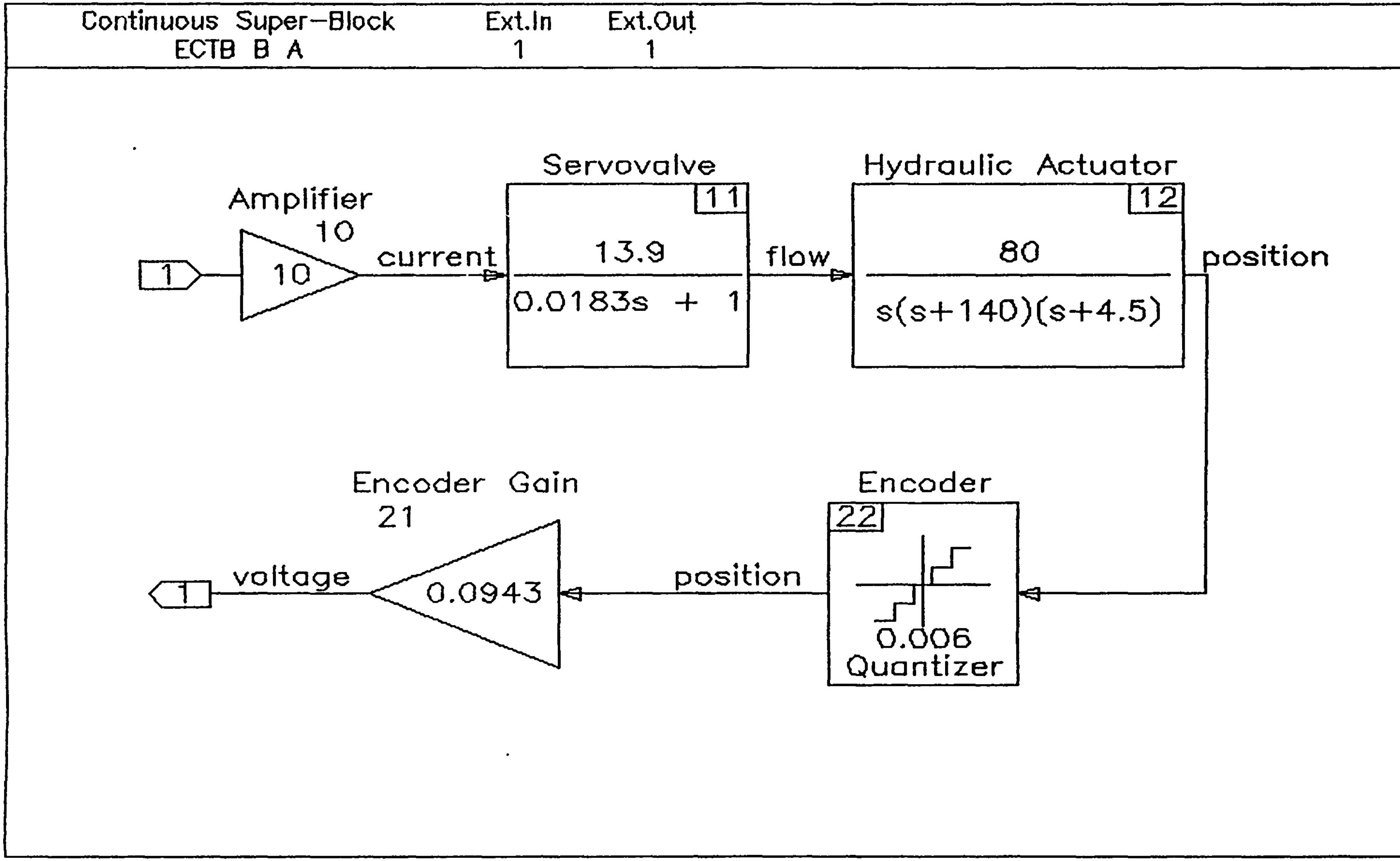

Figure B-4. Baseline Control System open loop block diagram.

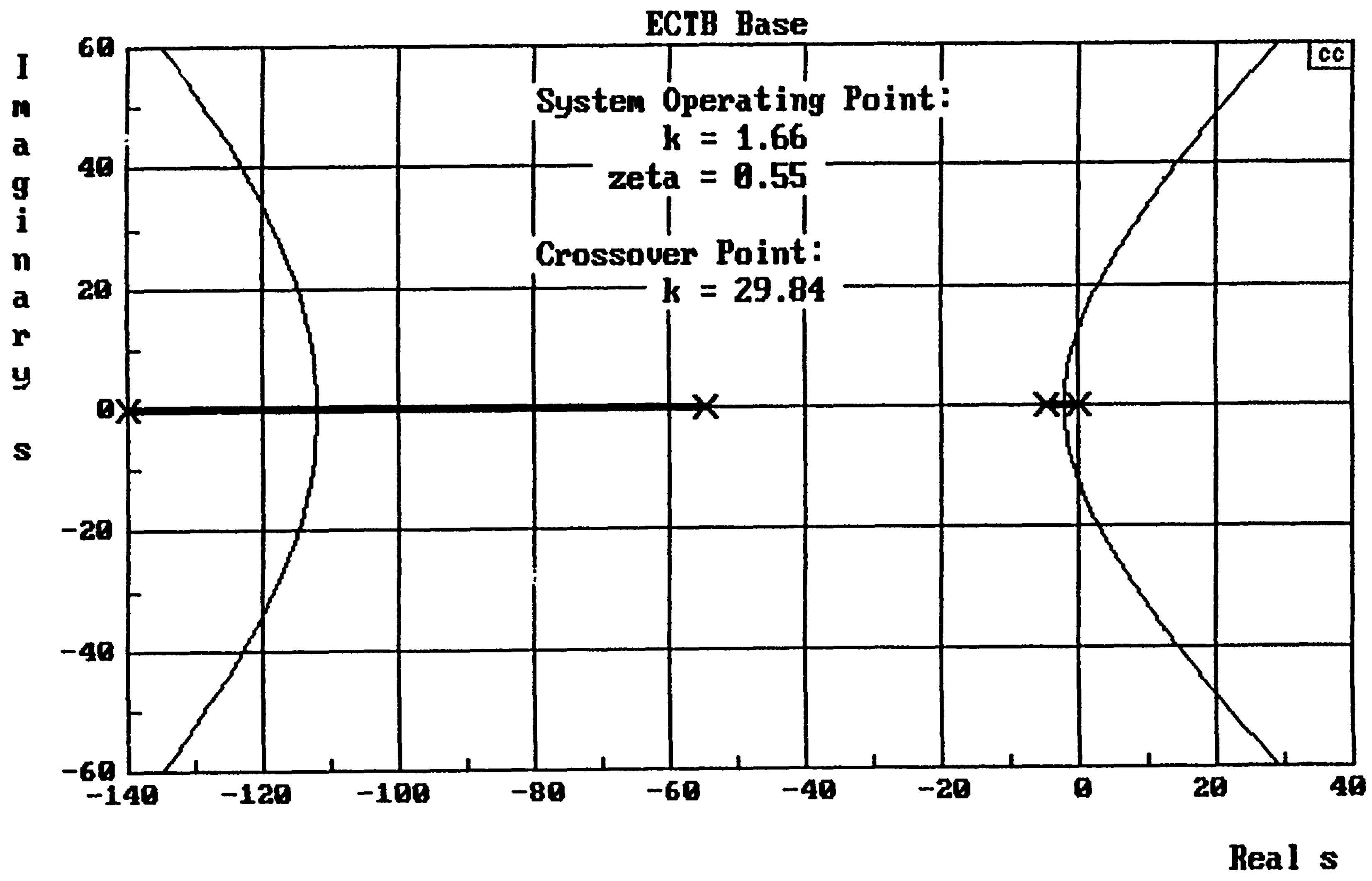

Figure B-5. Root locus - Baseline Control System.

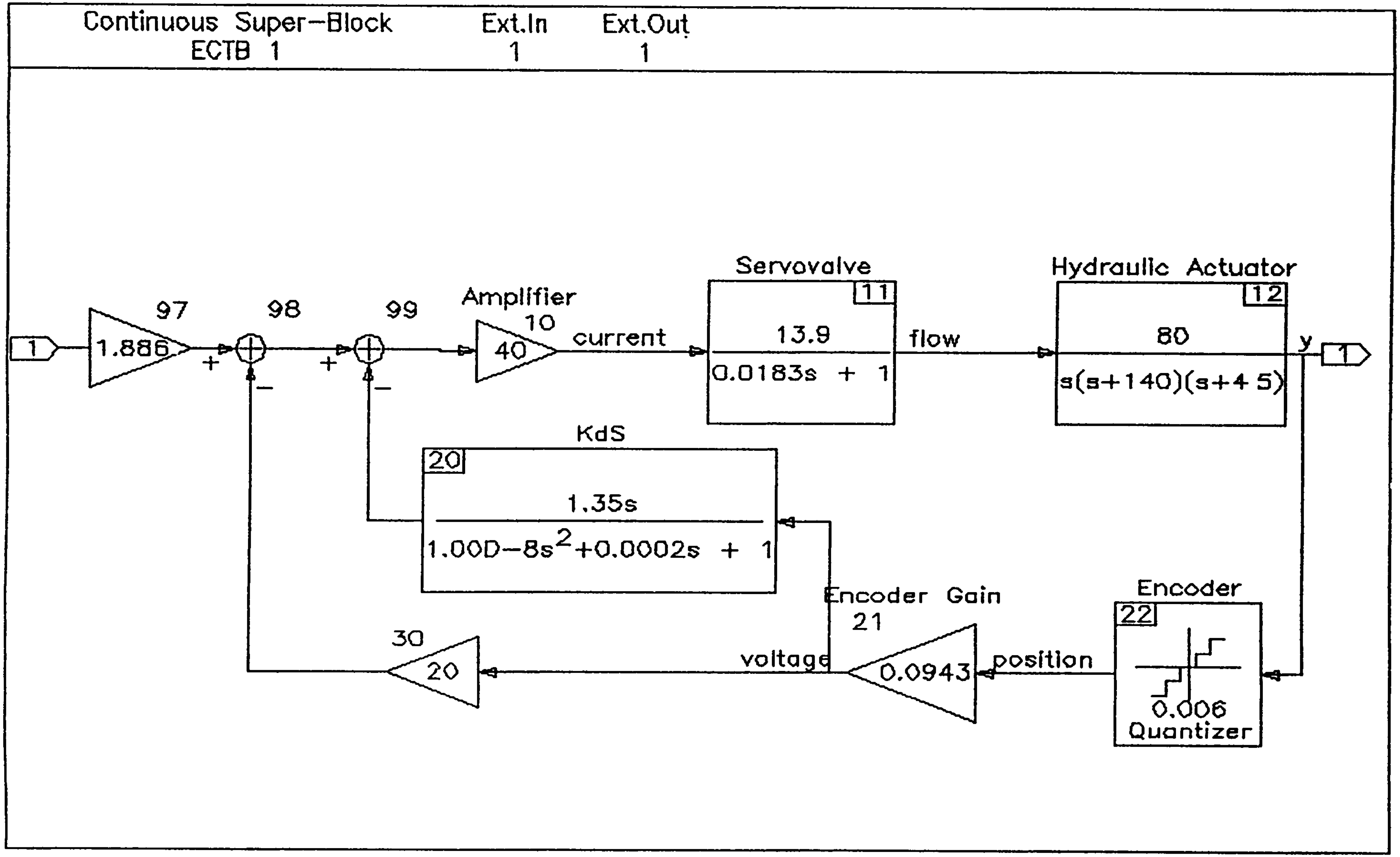

Figure B-6. Configuration No. 1 - Control System block diagram.

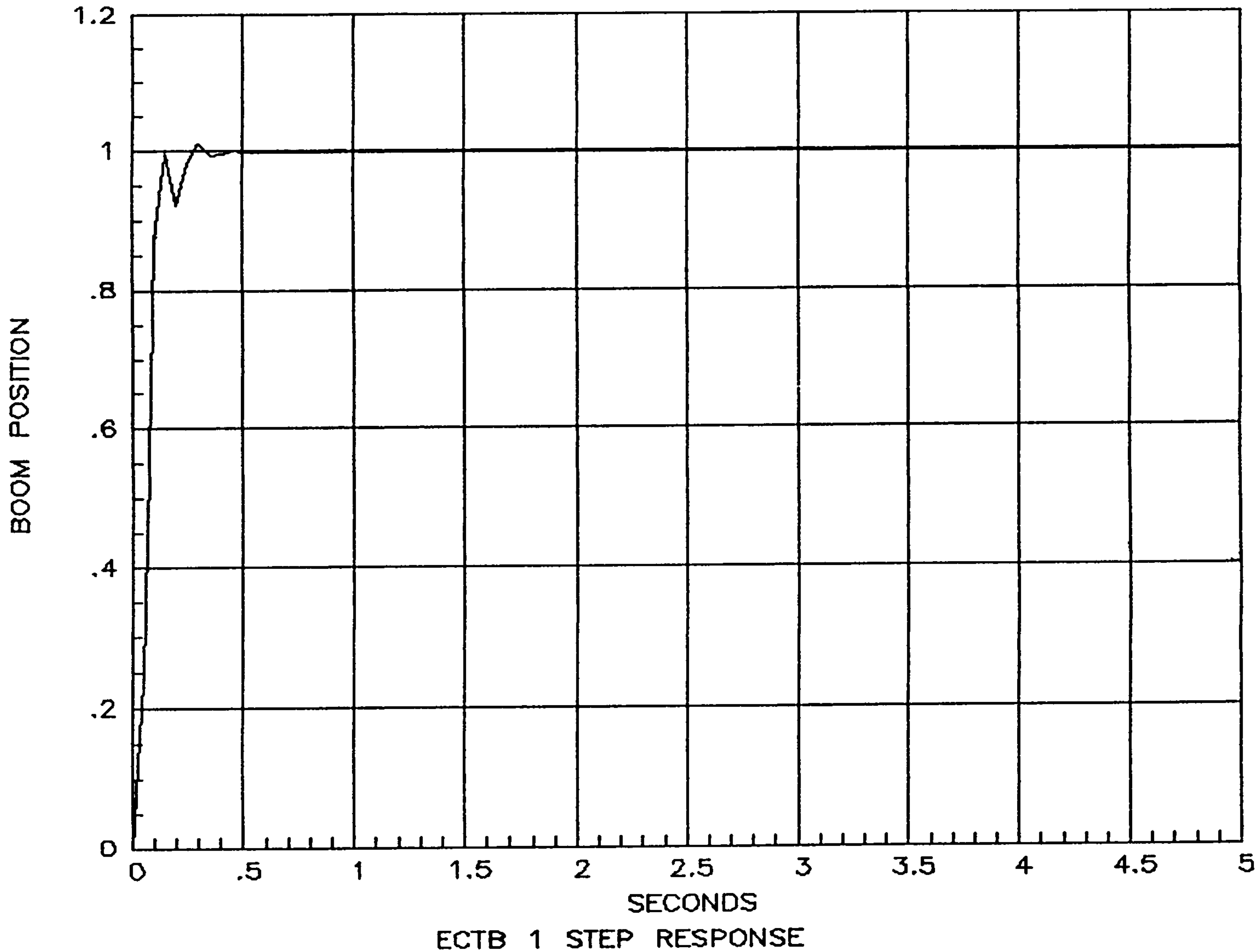

Figure B-7. Configuration No. 1 - Control System response.

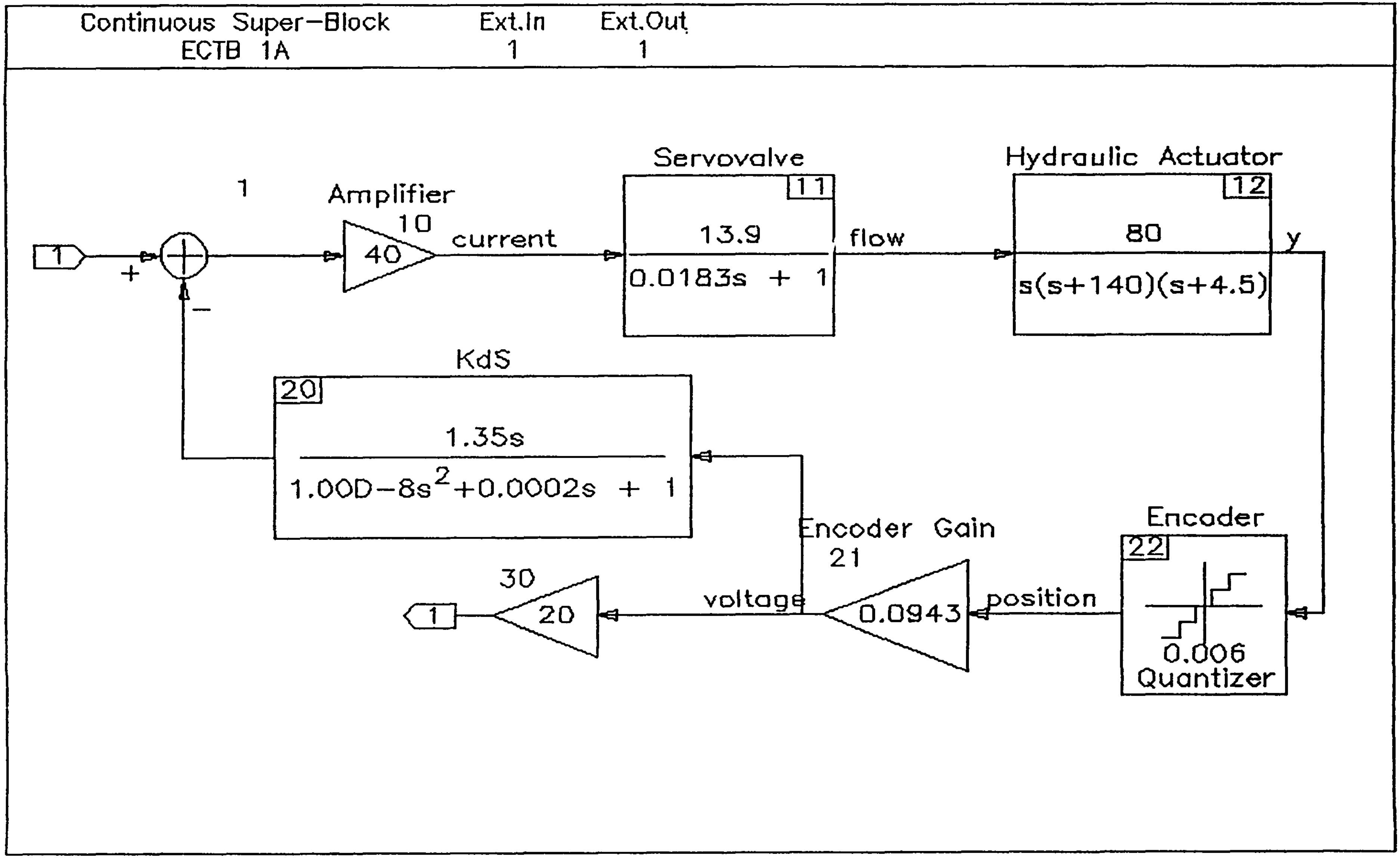

Figure B-8. Configuration No. 1 - Control System open-loop block diagram.

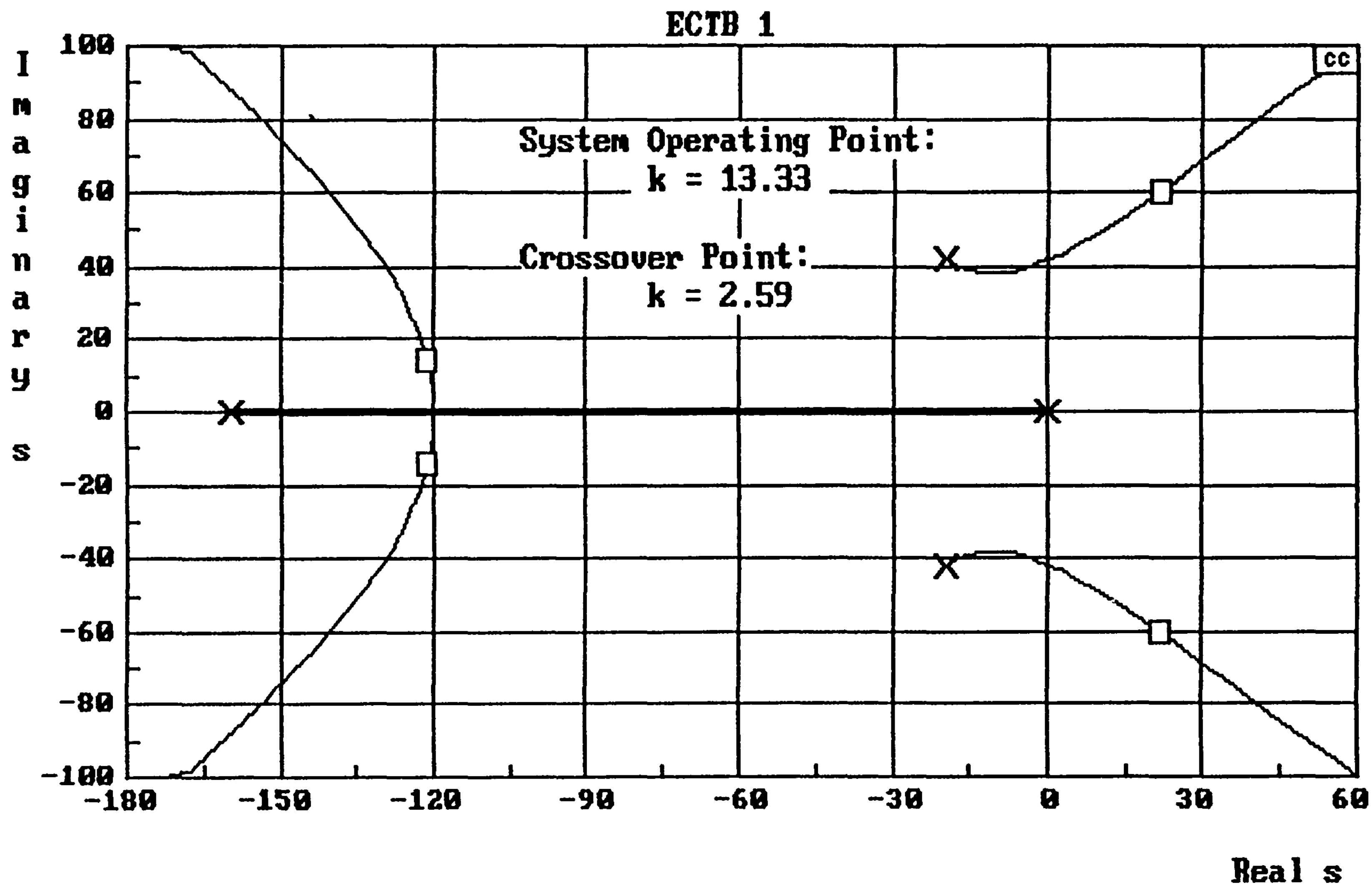

Figure B-9. Root locus - Configuration No.1 Control System.

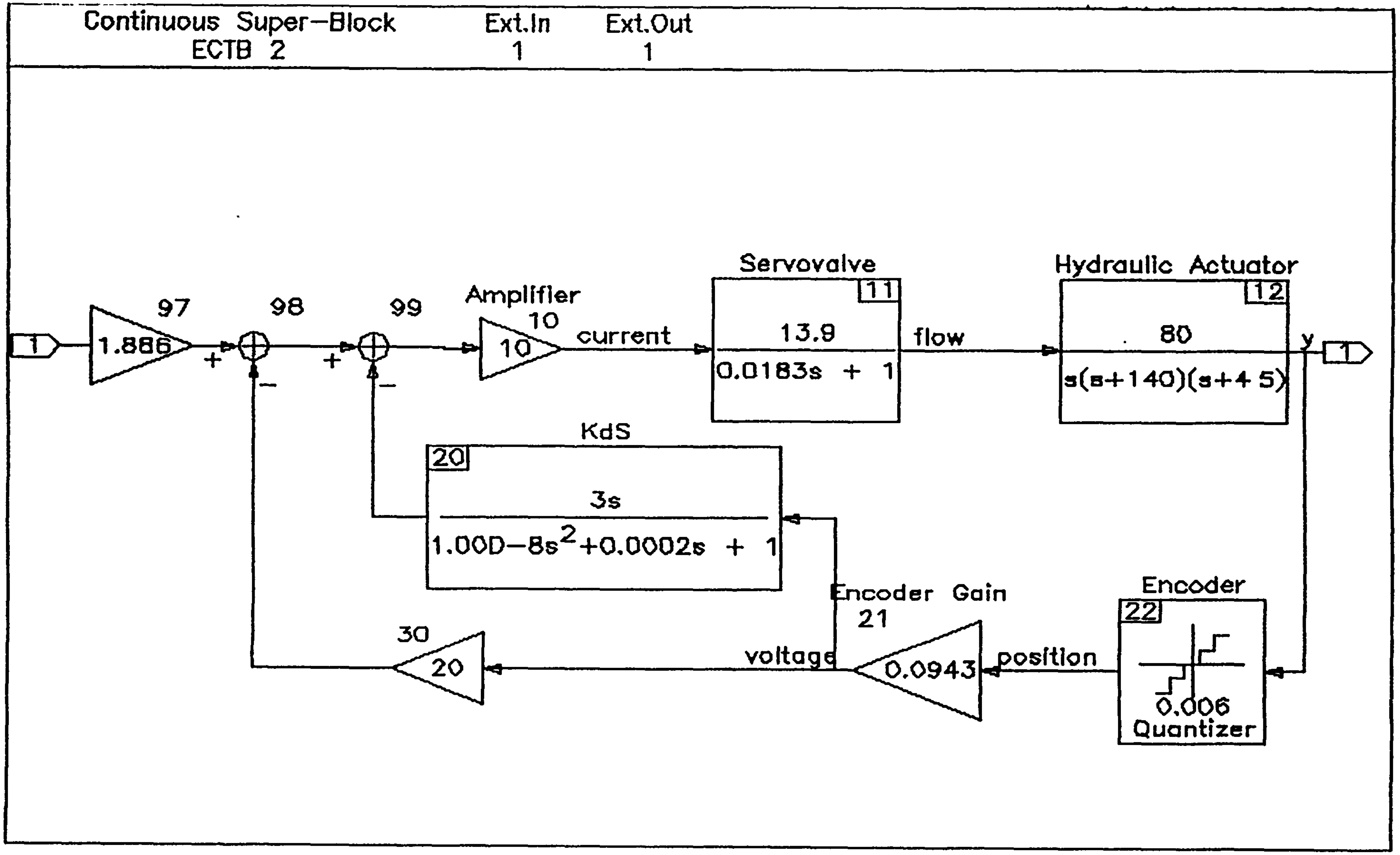

Figure B-10. Configuration No. 2 - Control System block diagram.

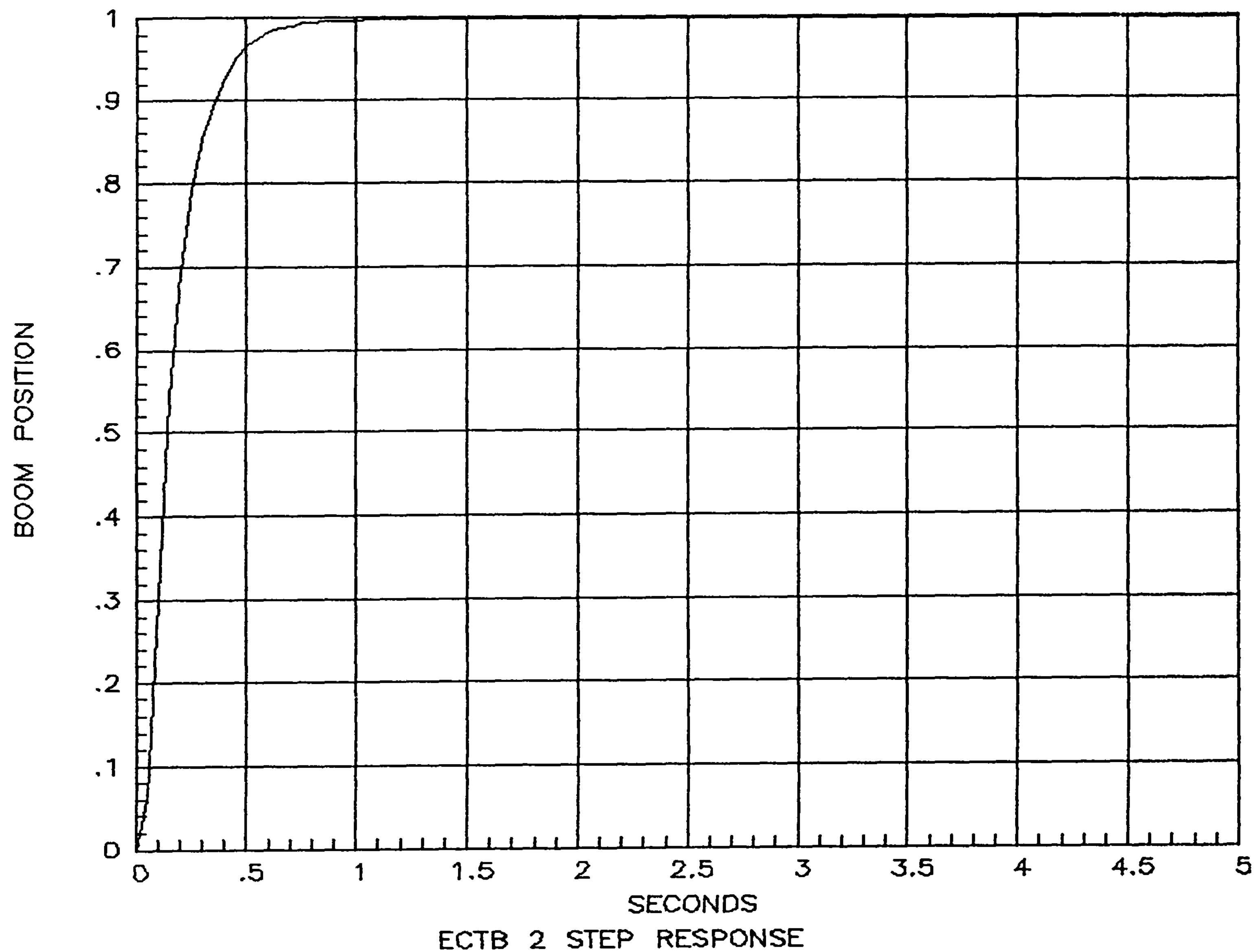

Figure B-11. Configuration No. 2 - Control System response.

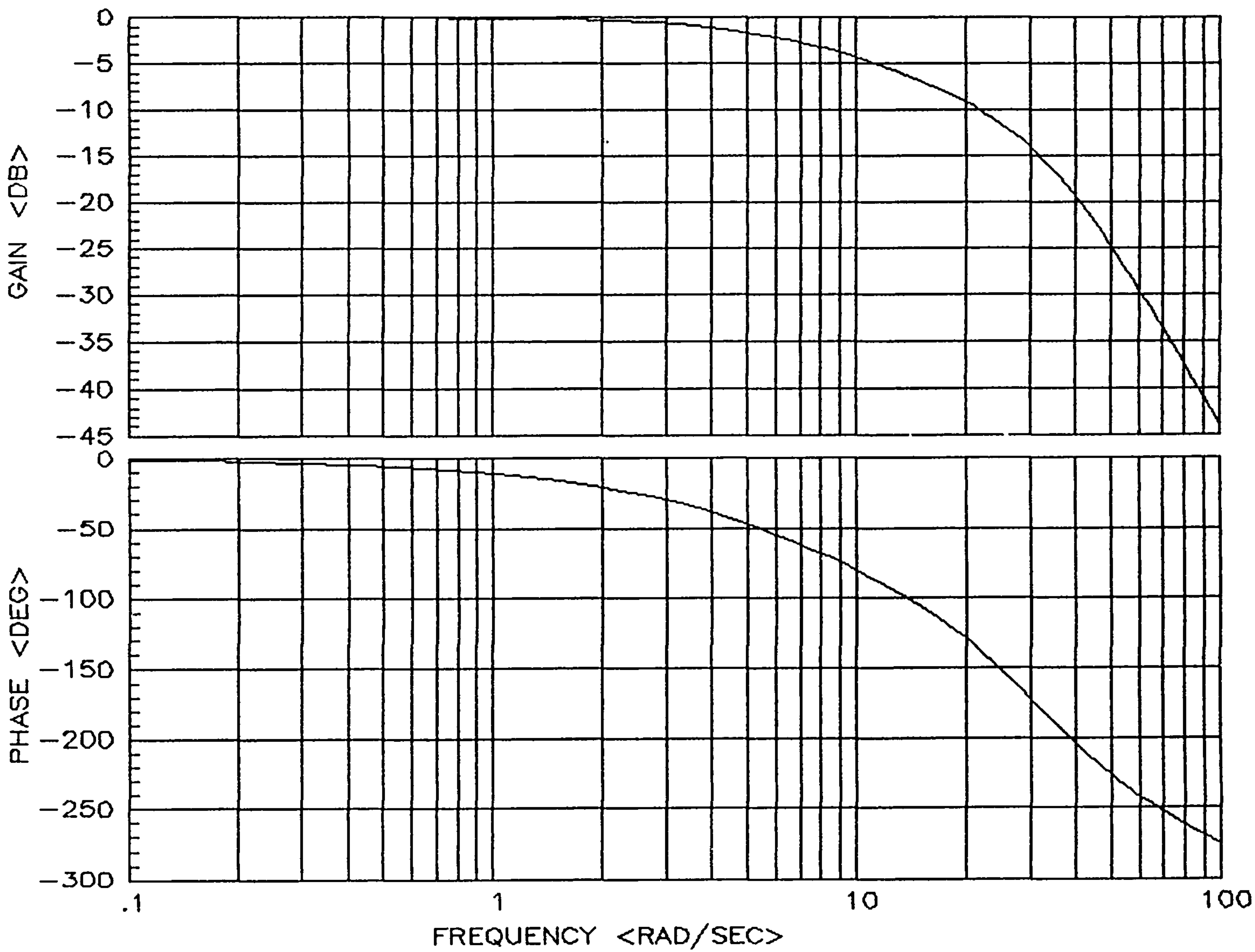

Figure B-12. Closed loop frequency response - Configuration No. 2 Control System.

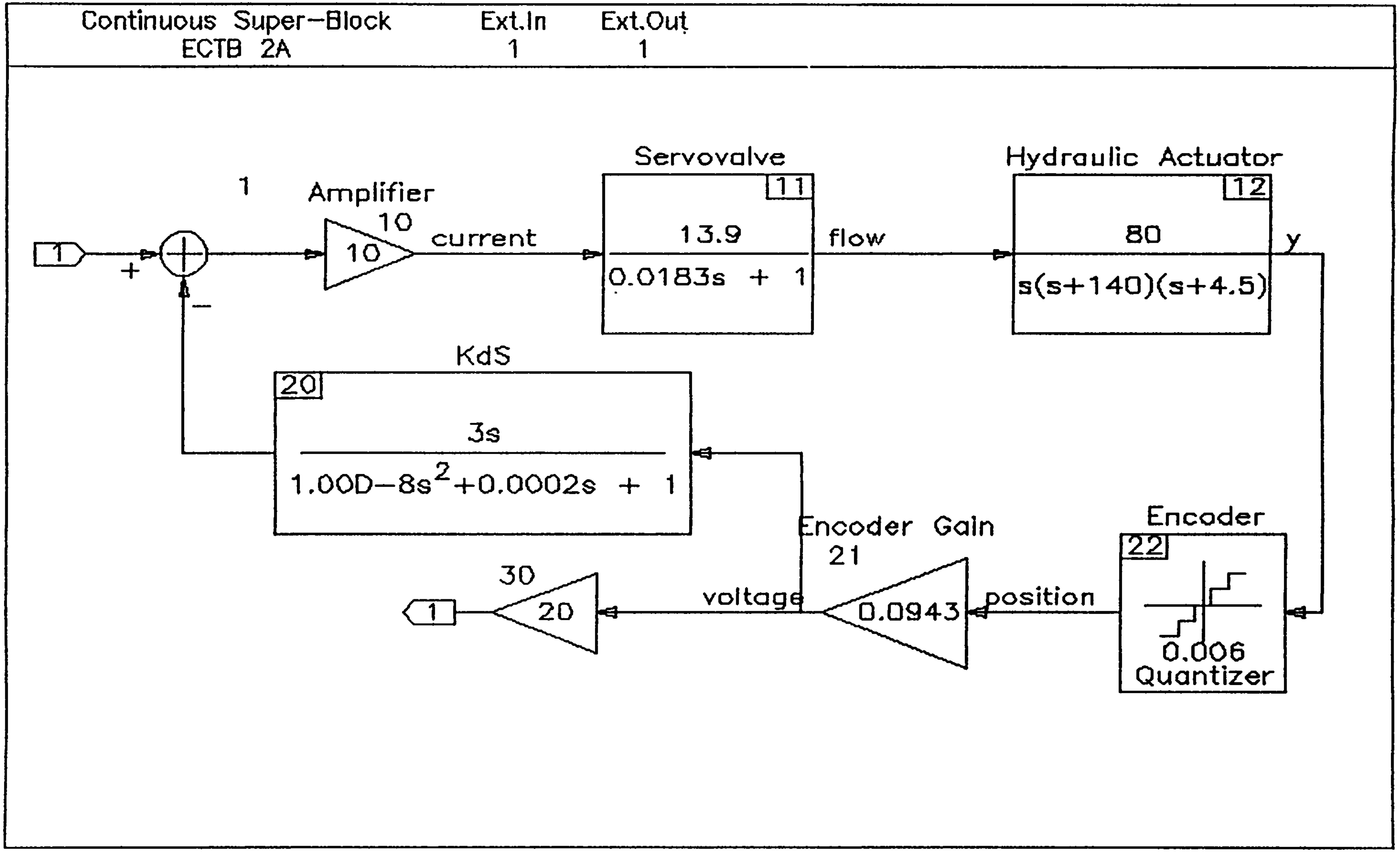

Figure B-13. Configuration No. 2 - Control System open-loop block diagram.

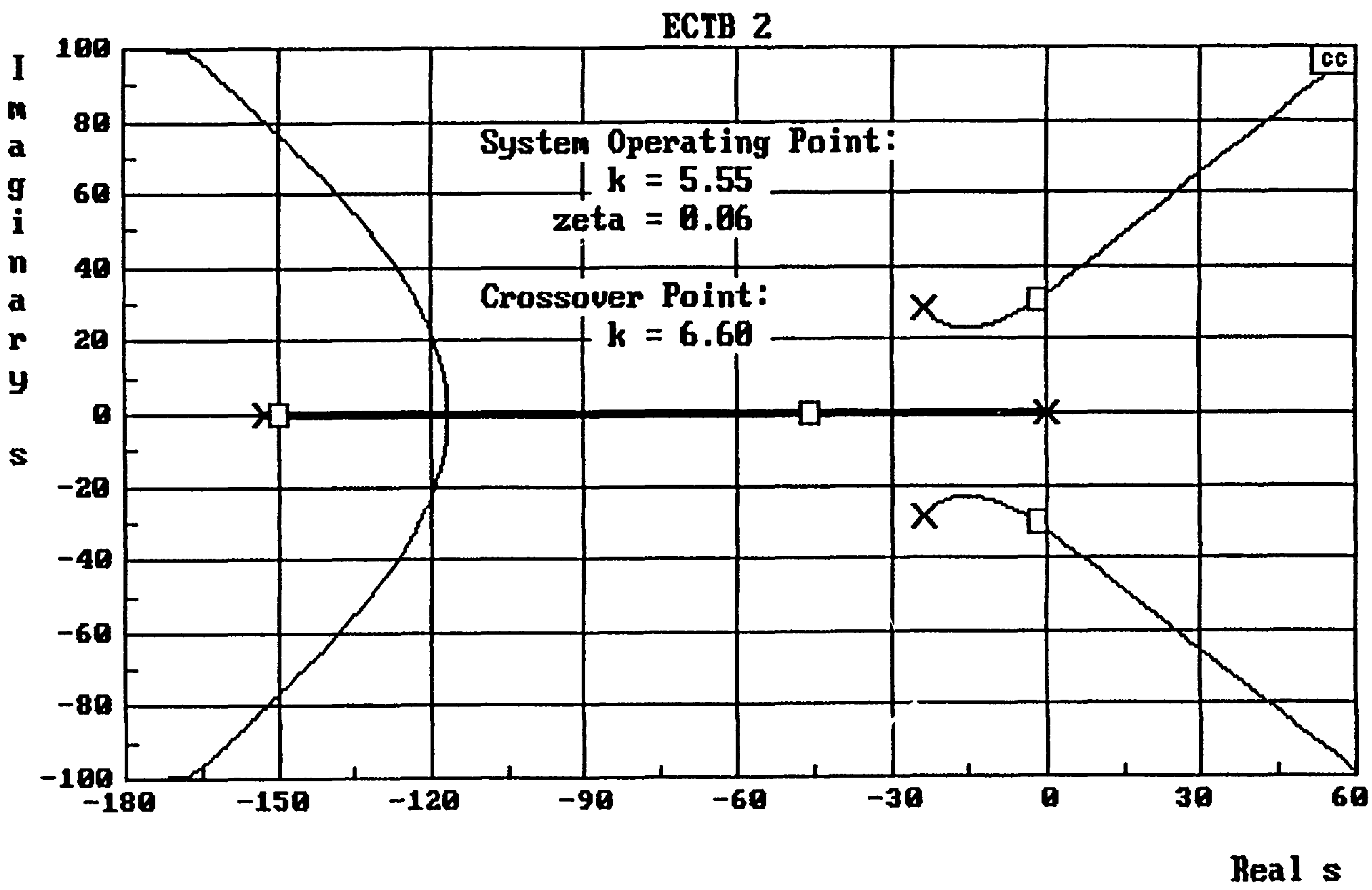

Figure B-14. Root locus - Configuration No. 2 Control System.

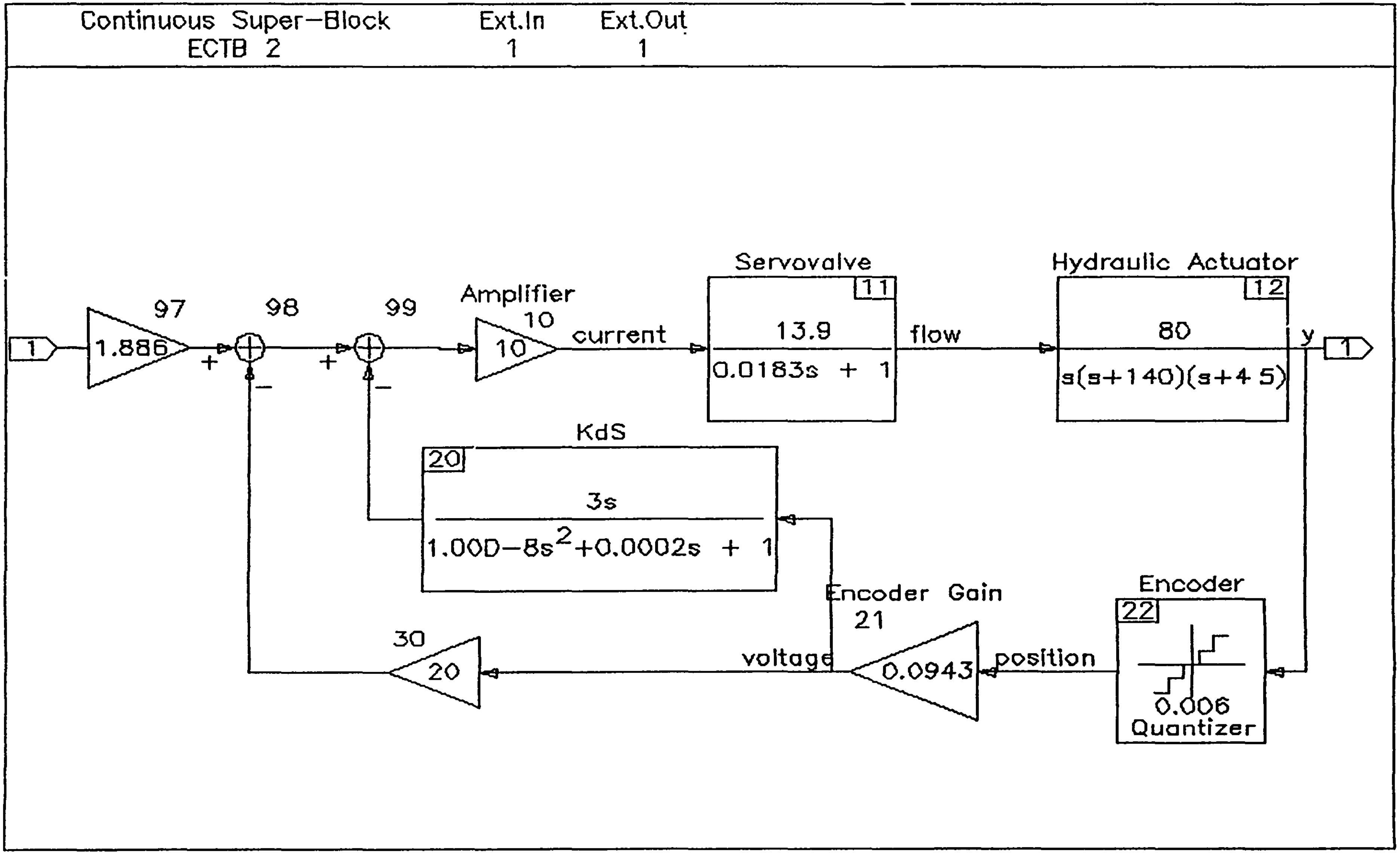

Figure B-15. Configuration No. 3 - Control System block diagram.

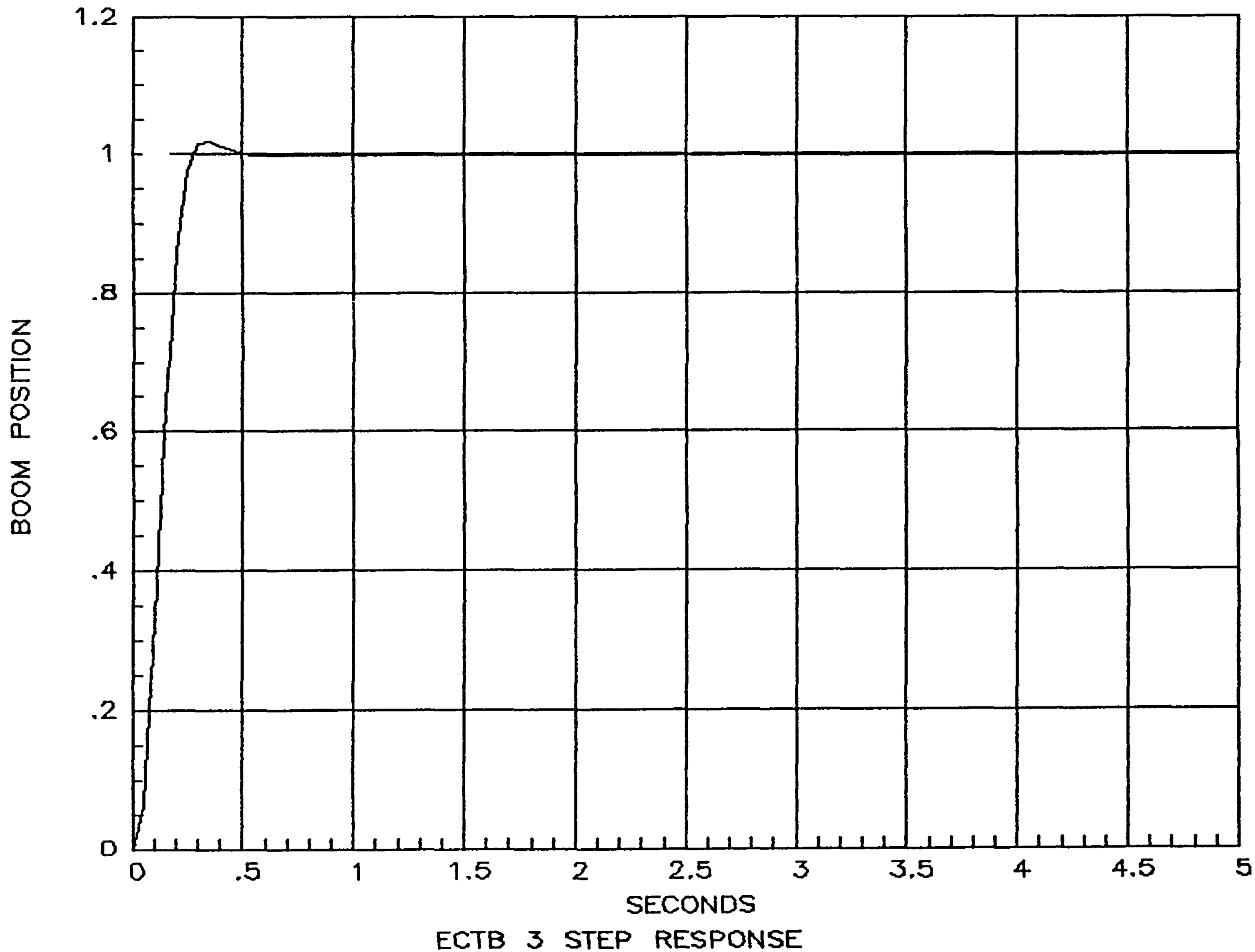

Figure B-16. Configuration No. 3 - Control System response.

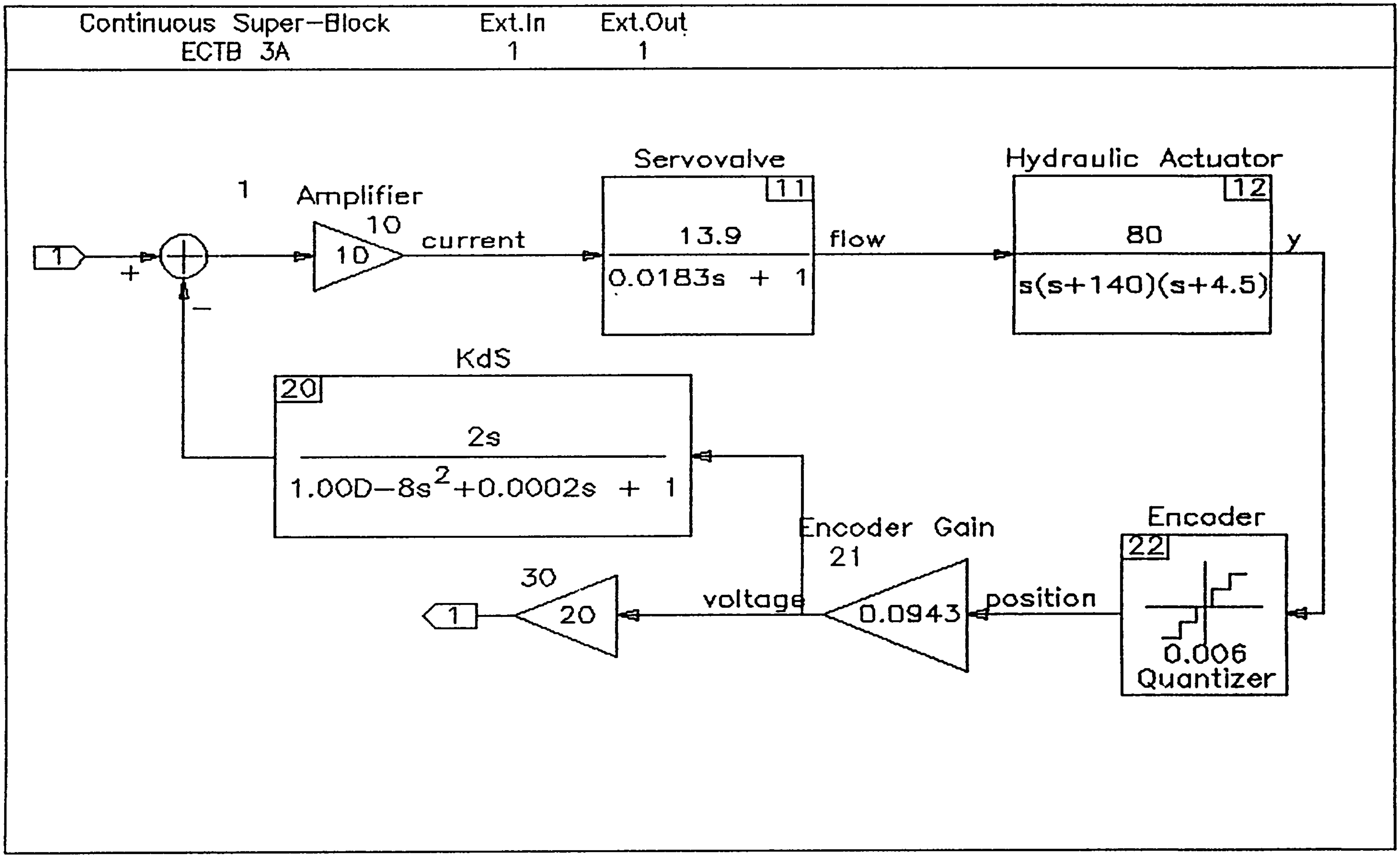

Figure B-17. Configuration No. 3 - Control System open-loop block diagram.

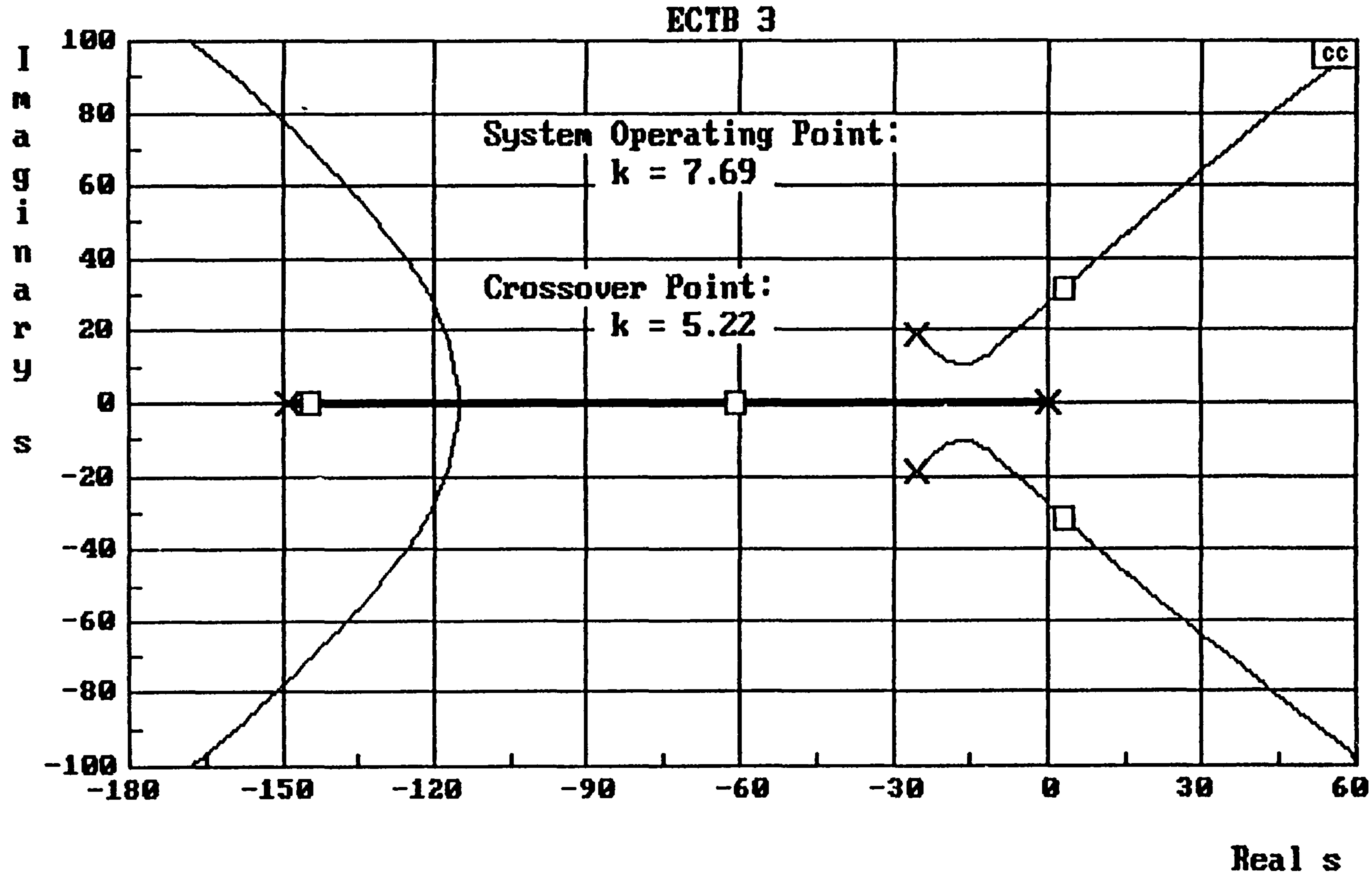

Figure B-18. Root locus - Configuration No. 3 Control System.

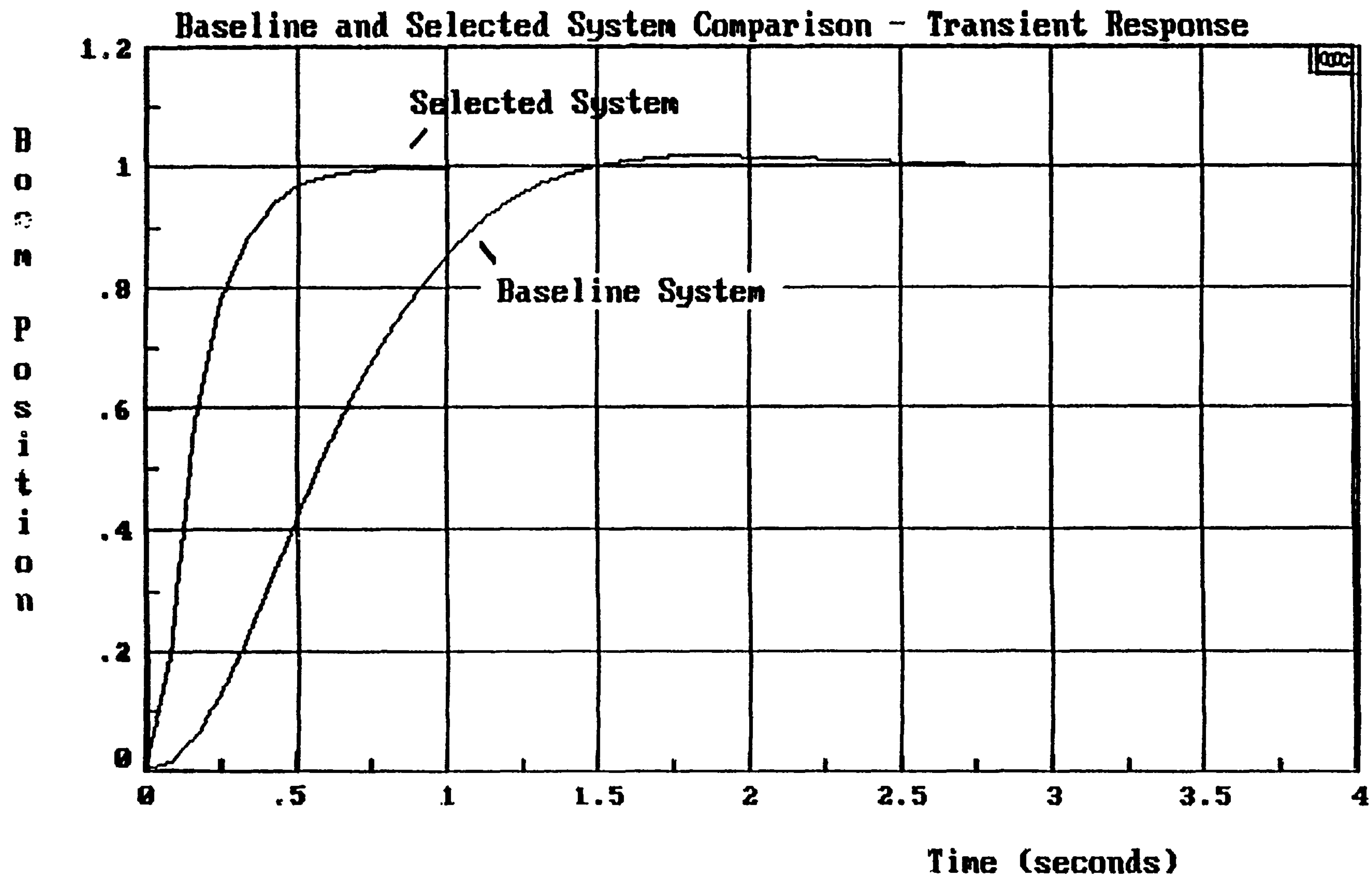

Figure B-19. Comparison of Step Responses, Baseline and Selected (Configuration No. 2) Control Systems.

Appendix C

ABBREVIATIONS AND ACRONYMS

AE	Assault Echelon
AFB	Air Force Base
AFESC	Air Force Engineering and Services Center
AOA	Amphibious Objective Area
ATLAS	All Terrain Lifter Articulated System
BRDEC	Belvoir Research, Development and Engineering Center
CACSD	Computer Aided Control System Design
CALAS	Computer Aided Load Acquisition System
CE	Construction Equipment
CMU	Carnegie Mellon University
D/A	Digital/Analog
DOD	Department of Defense
EBFL	Extendable Boom Forklift
ECTB	Equipment Controls Test Bed
FMR	Field Material Handling Robot
FY90	Fiscal Year 1990
HEL	Human Engineering Laboratory
HSC	High Speed Control
ITC	International Telepresence Corp.
MCRDAC	Marine Corps Research, Development and Acquisition Command
MEF	Marine Expeditionary Force
MHE	Material Handling Equipment
NBC	Nuclear, Biological and Chemical
NCEL	Naval Civil Engineering Laboratory
ORNL	Oak Ridge National Laboratory
PASS	Pallet Acquisition Sensor System
R&D	Research and Development
RRR	Rapid Runway Repair
SMCC	Smart Motion Control Card
USMC	U.S. Marine Corps

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ARMY FEAP
BDG Shore Facilities
NRG Energy
ENV Environmental/Natural Responses
MGT Management
PRR Pavements/Railroads

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